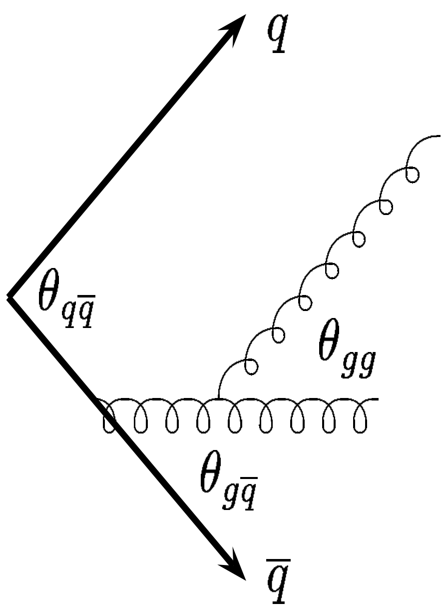
Color Coherence Results

Nikos Varelas

University of Illinois at Chicago



$$\theta_{gg} < \theta_{g\bar{q}} < \theta_{q\bar{q}}$$

XVIII Physics in Collision

June 17 - 19, 1998

Frascati

Color Coherence

In QCD: Interference of soft gluon radiation emitted along color connected partons.

Intrajet Coherence

- Angular Ordering of sequential branchings in a partonic cascade
- *Hump-backed* shape of particle spectra

Interjet Coherence

String or Drag effect in multijet hadronic events

Shower Development

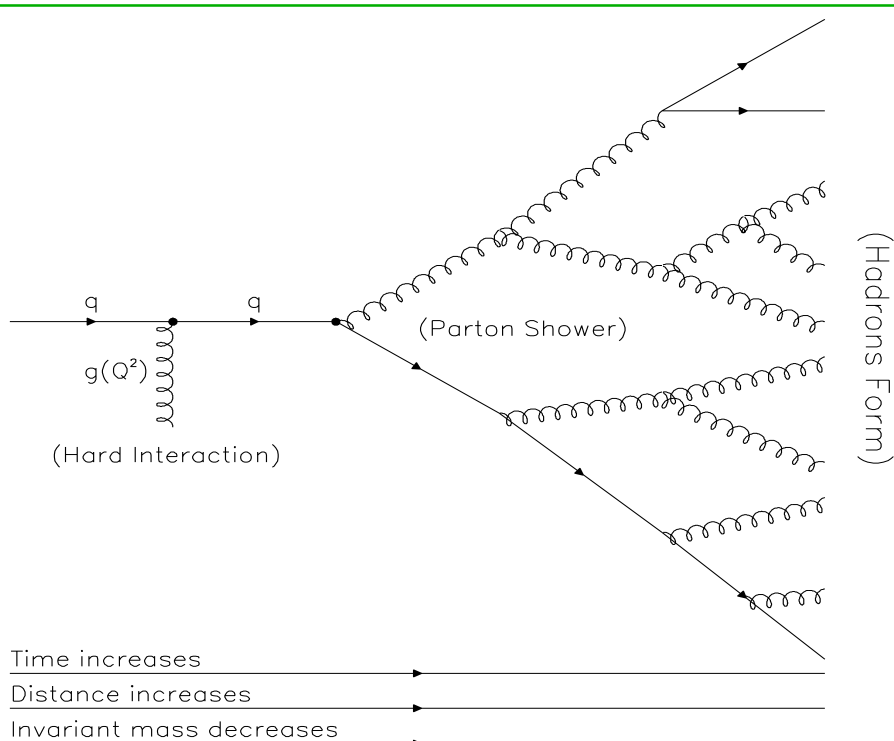
"Traditional Approach"

- Shower develops according to pQCD into jets of partons until a scale of $Q_0 \sim 1$ GeV.
- Thereafter, non-perturbative processes take over and produce the final state hadrons

"Local Parton Hadron Duality (LPHD) Approach"

- Parton cascade is evolved further down to a scale of about $Q_0 \sim 250$ MeV.
- No hadronization process.

  Hadron spectra = Parton spectra
- Simplicity. Only two essential parameters (Λ_{QCD} and Q_0) and an overall normalization factor

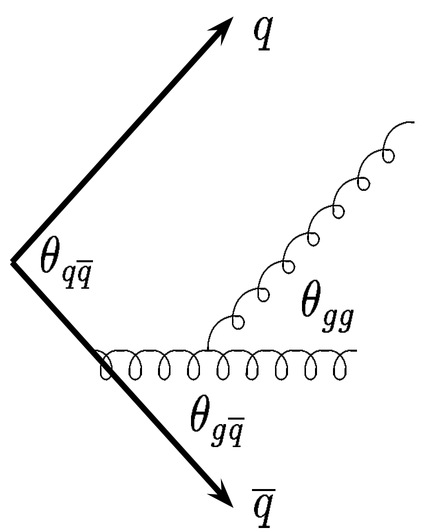


Intrajet Coherence

- Color Coherence (CC) effects in partonic cascades

- Angular Ordering Approximation

> uniform *decrease* of successive emission angles of soft gluons as partonic cascade evolves away from the hard process



$$\theta_{gg} < \theta_{g\bar{q}} < \theta_{q\bar{q}}$$

Intrajet Coherence

Theoretical Framework:

- Analytic Approach:

PQCD + LPHD → **DLA, MLLA...**

LPHD ⇒ at low evolution scales the hadronic distributions are expected to be proportional to the partonic ones

PQCD ⇒ Resummed analytical calculations (DLA, MLLA) incorporate leading coherence effects

- MC Approach:

Perturbative: Include CC effects probabilistically by means of AO for both initial and final state evolutions

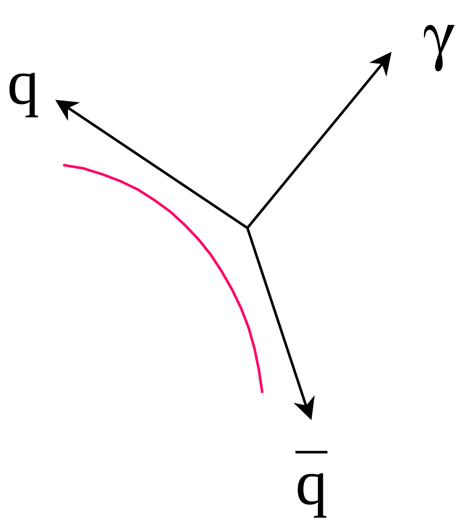
Non-Perturbative: Use phenomenological models to simulate the non-perturbative hadronization stage, e.g. the LUND string model or the cluster fragmentation model.

Interjet Coherence

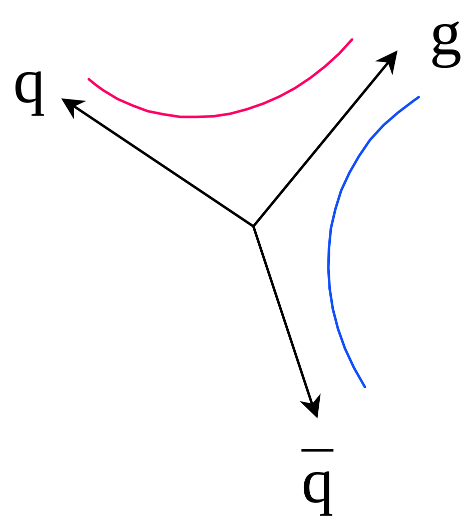
- Interjet coherence deals with the angular structure of particle flow when three or more partons are involved

- **e^+e^- interactions:**

First observations of final state color coherence effects in the early '80's (**"string"** or **"drag"** effect)



$e^+e^- \to q\,\bar{q}\,\gamma$



$e^+e^- \to q\,\bar{q}\,g$

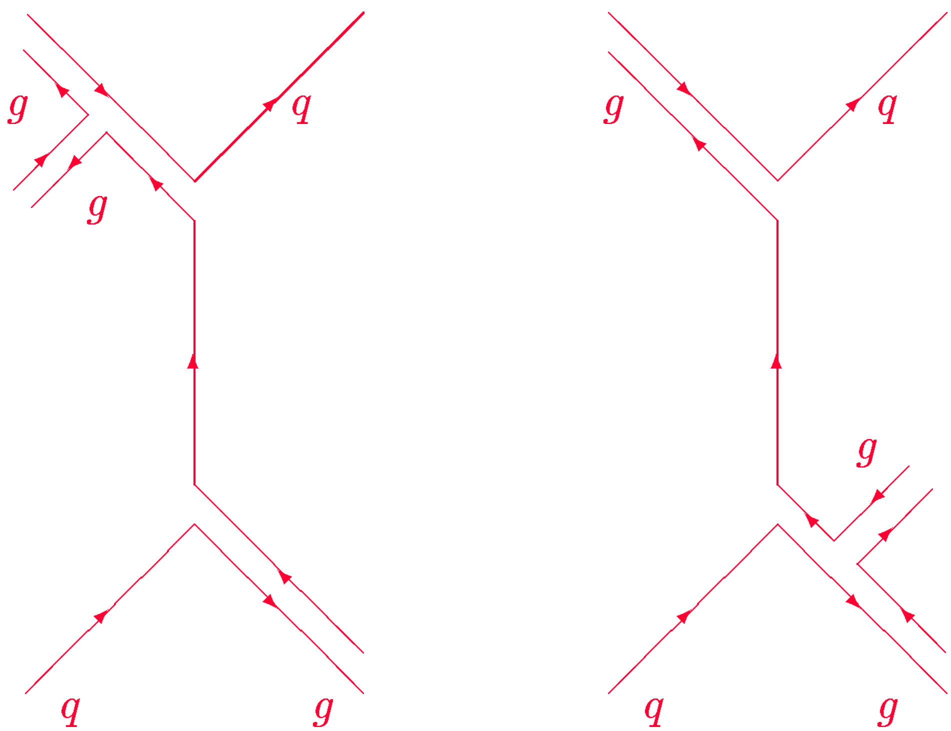
Depletion of particle flow in region between q and $\bar{q}$ jets relative to that between q and g jets.

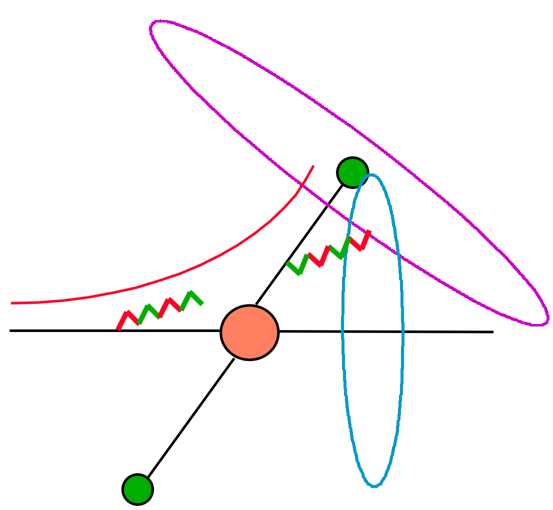
Interjet Coherence

$p\bar{p}$ interactions:

• Colored constituents in initial *and* final state (more complicated that e^+e^-)

• Probes initial-initial, final-final and **initial-final** state color interference





Recent Results

Intrajer Coherence

- ☞ Hump-backed plateau
- ☞ Invariant charged hadron energy spectrum
- ☞ Angular multiplicity fluctuations in hadronic Z decays (L3 Analysis - CERN-EP/98-23) - not shown -

Interjer Coherence

- ☞ Multijets
- ☞ Particle flow in W+Jets events

- ☞ Color reconnection effects in $e+e^- \rightarrow q\bar{q}g$ events

- Experimental issues:

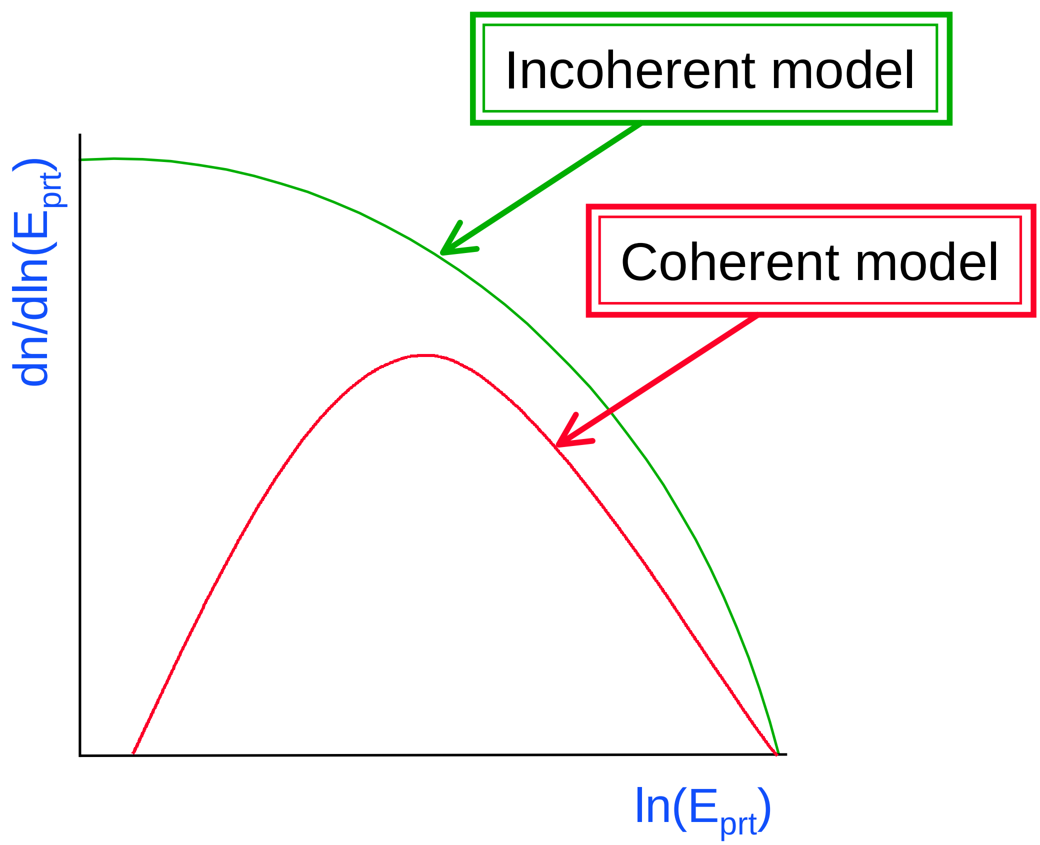
  ★ Can Color Coherence effects survive hadronization process?

  ★ What is relative importance of perturbative vs. non-perturbative contributions?

Hump-backed plateau

- Direct consequence of CC+LPHD
- Depletion of soft particle production within jets
- Approximately Gaussian shape of inclusive distribution in the variable $\xi=\ln(E_{jet}/E_{prt})=\ln(1/x)$
- The height of the *hump* is increasing with energy and peaks at $E_{prt} \sim E_{jet}^{0.5}$
- Analytic calculations: MLLA+LPHD

$$\frac{1}{\sigma}\frac{d\sigma}{d\xi_p} = K_{LPHD} \bullet f\left(\xi_p, Y, \lambda\right) \qquad Y = \log\frac{\sqrt{s}}{Q_0} \; ; \; \lambda = \log\frac{Q_0}{\Lambda}$$



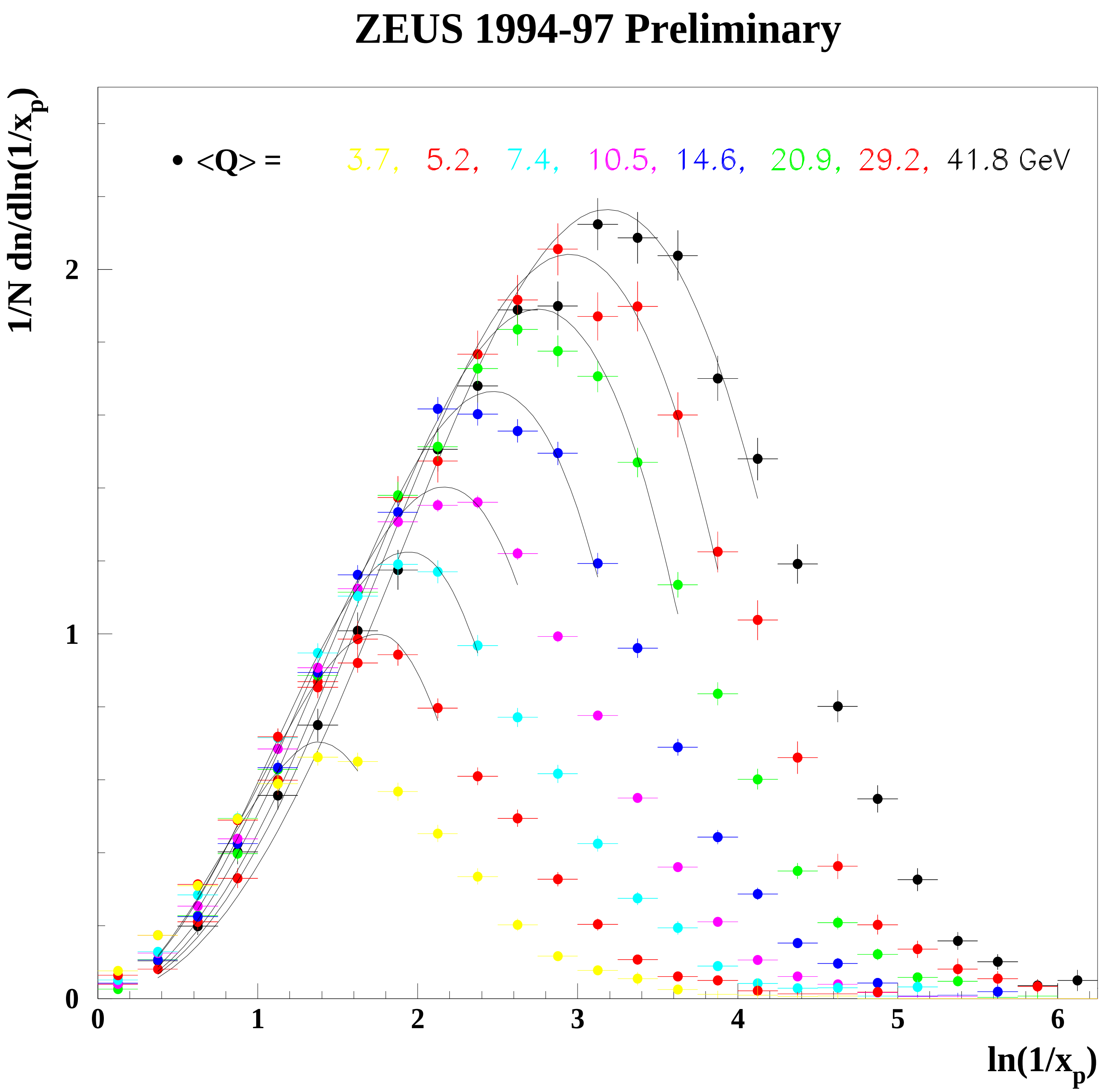
Hump-backed plateau
Results

Charged hadron inclusive fragmentation functions

HERA

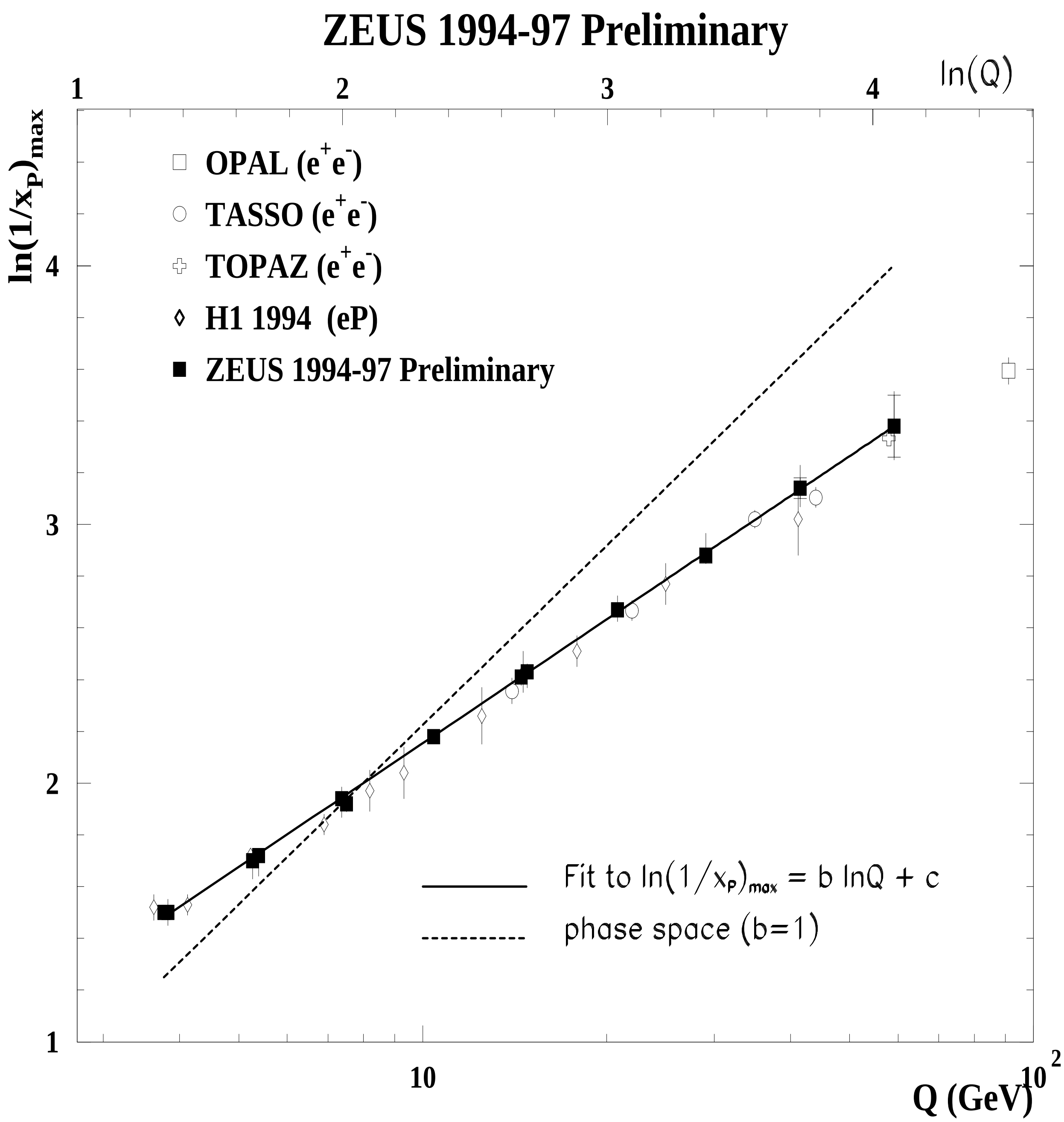
- P_T of tracks > 150 MeV/c
- Studies performed at the Breit Frame of Reference
- Concentrate on the "current" hemisphere of the interaction (fragmentation products of the outgoing quark)
- The DIS "current" fragmentation (CF) functions at a momentum transfer Q are analogous to the e^+e^- fragmentation functions at center of mass energy equal to Q
- Test of the universality of fragmentation functions

$\log(1/x_p)$ evolution



- MLLA curves fit data well
- clear increase of $\ln(1/x_p)_{max}$ and multiplicity with Q

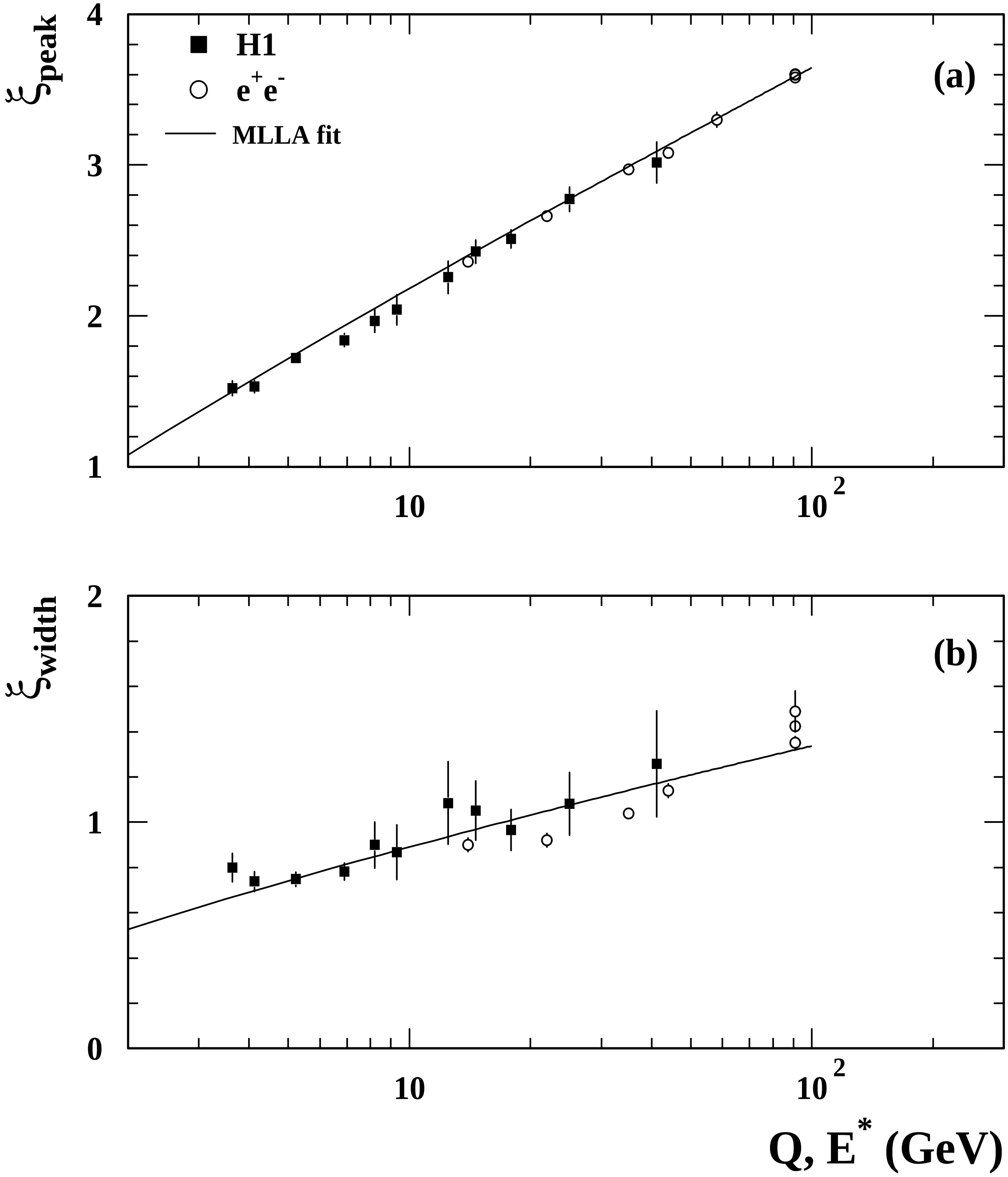
$\xi^* \ (\xi_{peak}) \equiv \log(1/x_p)_{max}$ evolution



- Incoherent fragmentation (phase space) excluded by both DIS & e^+e^-
- MLLA fit (not shown) with Y=log(Q/2Λ):

$$\boxed{\log(1/x_p)_{\max} = 0.5Y + c\sqrt{Y} - c^2 \Rightarrow \Lambda_{eff} \approx 245\,\mathrm{MeV}}$$

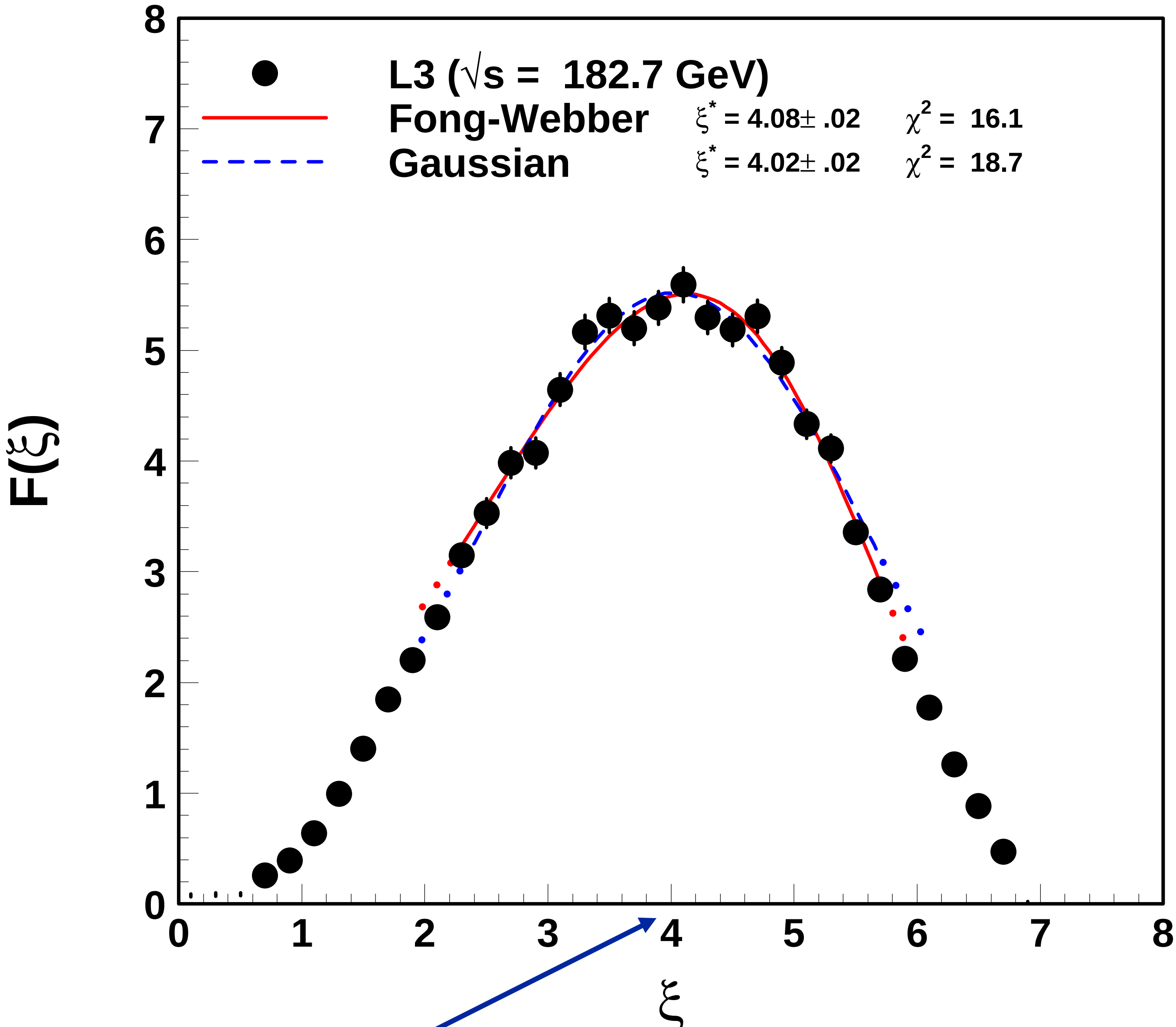
ξ_{peak} and ξ_{width} evolution



- MLLA predictions fit data well
- A simultaneous fit to the peak and width values of H1 data, yields a value of Λ_{eff}=0.21 ± 0.02 GeV, in agreement with LEP

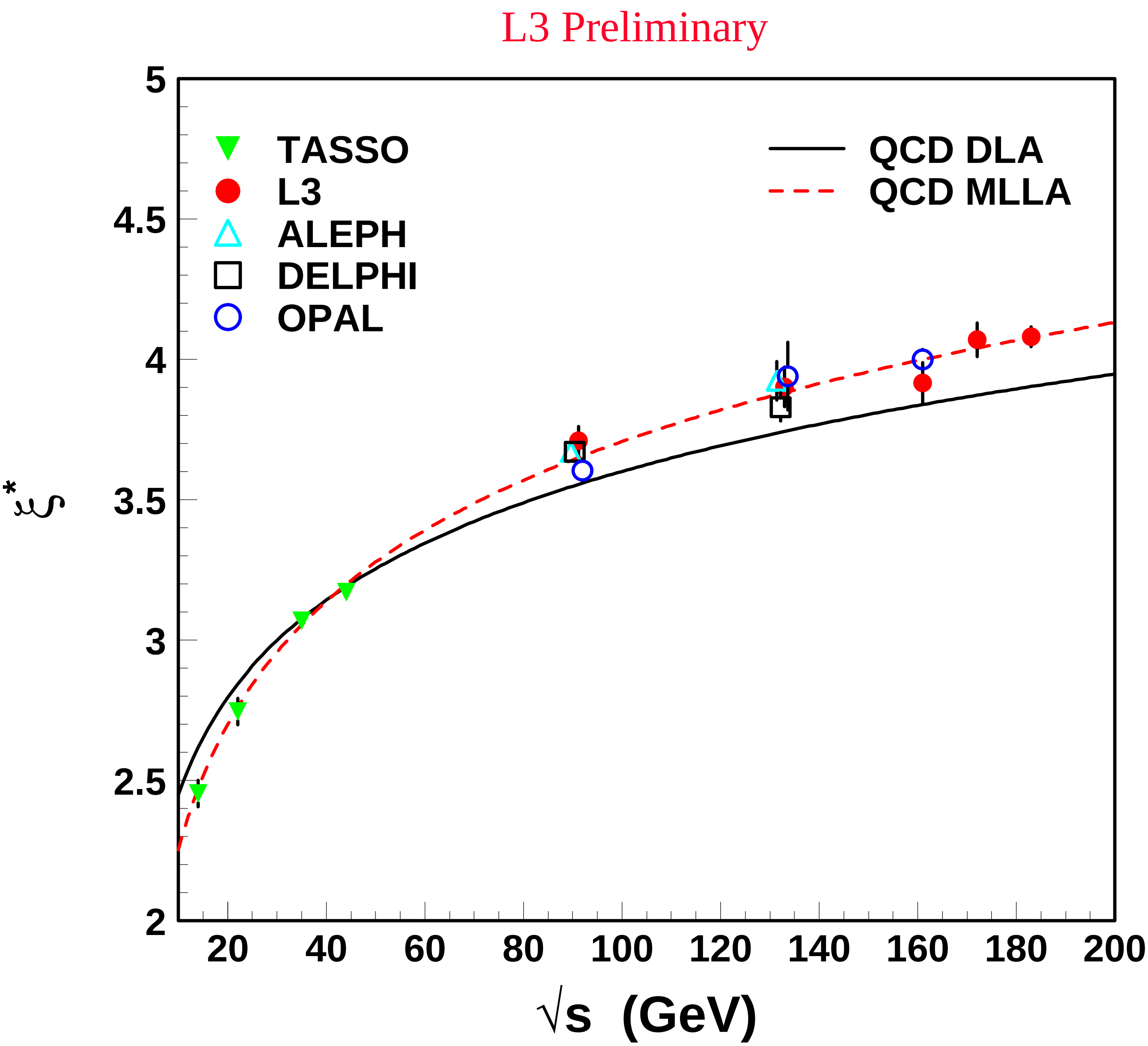
Results from LEP

log(1/x_p) evolution



$\xi^*(183\text{ GeV}) = 4.08 \pm 0.02 \pm 0.03$

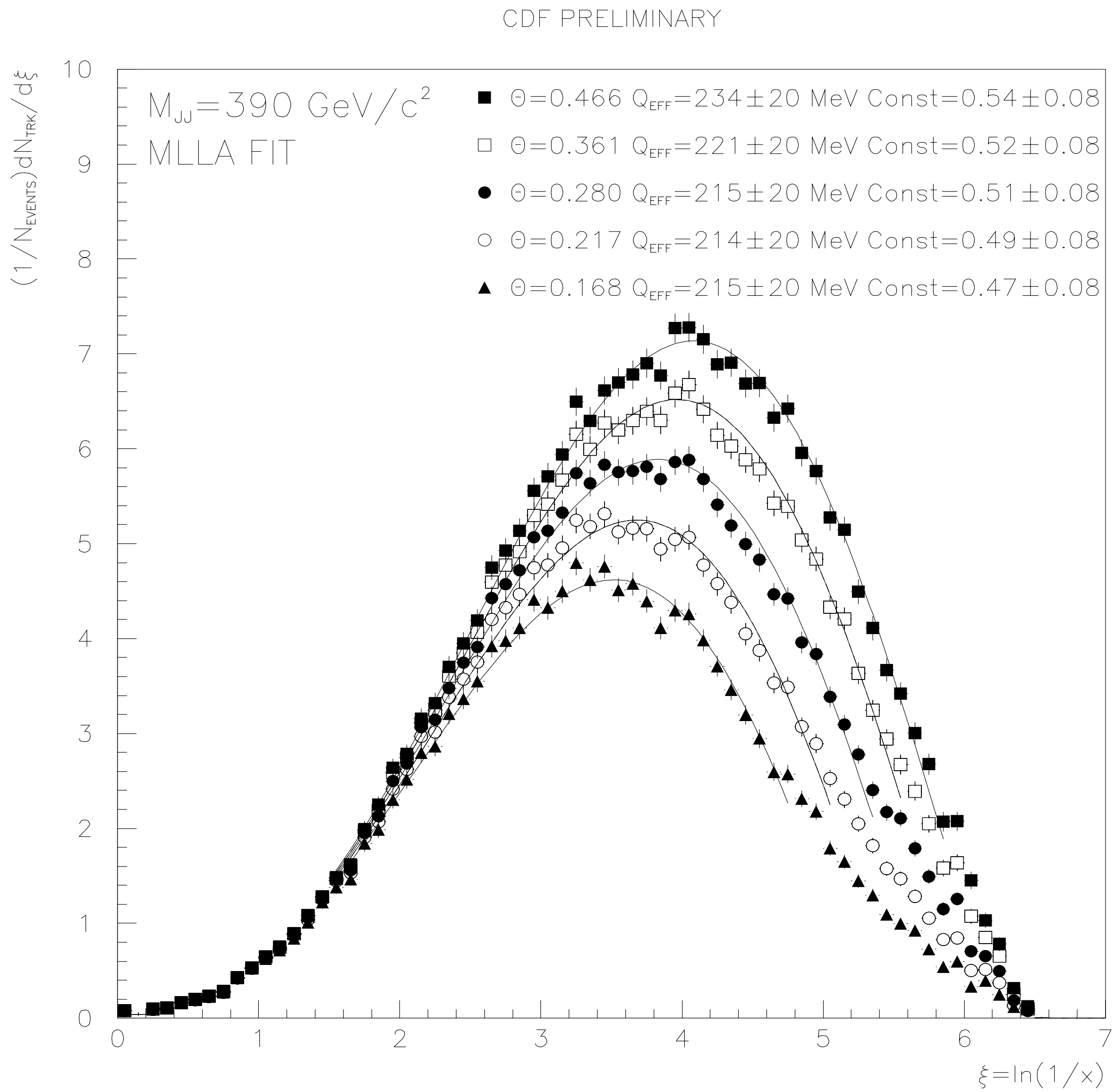
$\log(1/x_p)_{max}$ evolution



MLLA prediction fits the data better than DLA

Results from TEVATRON

$\log(1/x_p)$ evolution

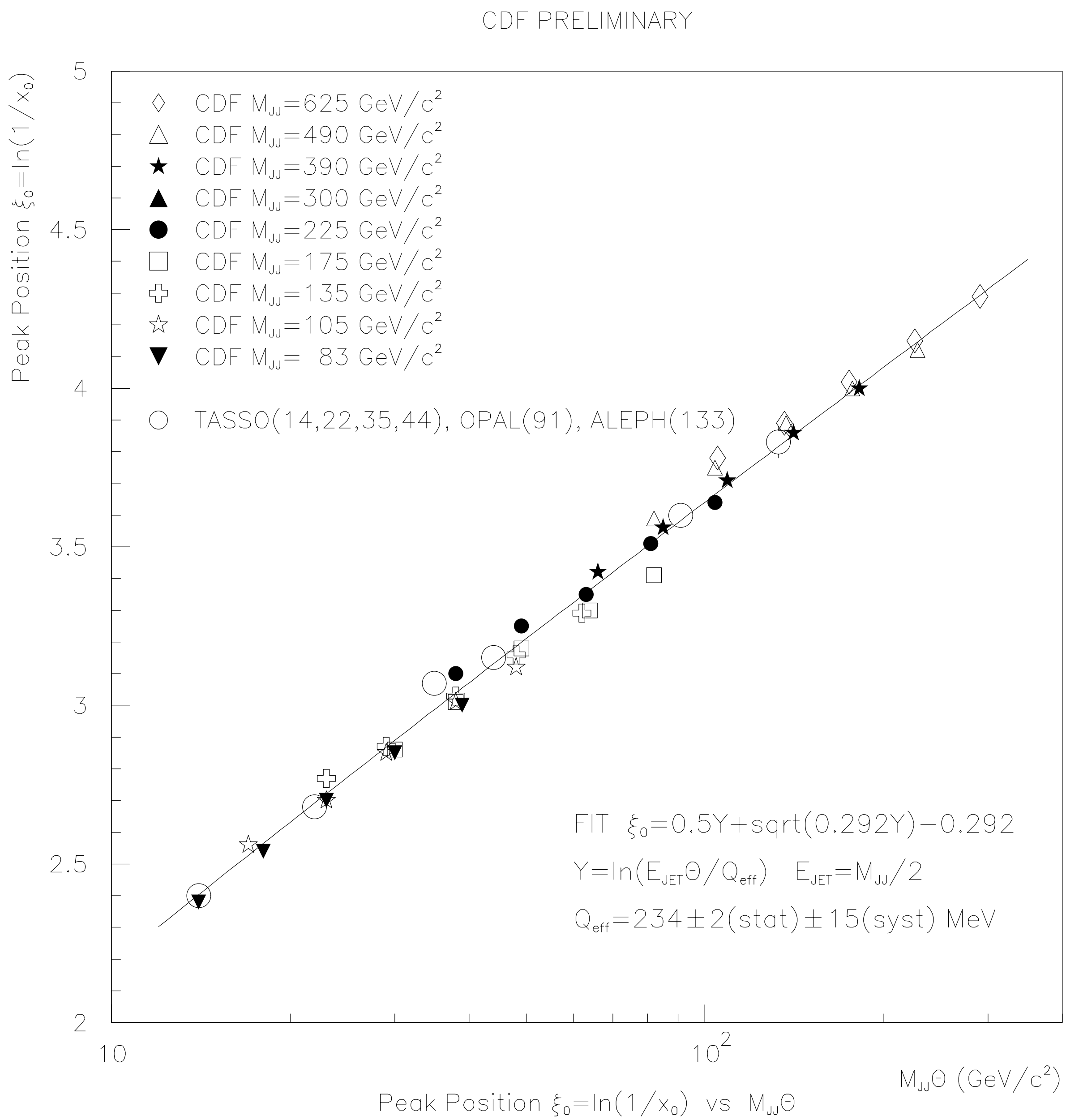


Dijet events: $E_{jet} = M_{jj}/2,\ Y = \ln\left(\frac{E_{jet}\cdot\theta_{cone}}{Q_{eff}}\right),\ \xi = \ln\frac{E_{jet}}{p_{trk}}$

$$Q_{eff} \equiv Q_0 = \Lambda_{QCD}$$

$\log(1/x_p)_{max}$ evolution

CDF

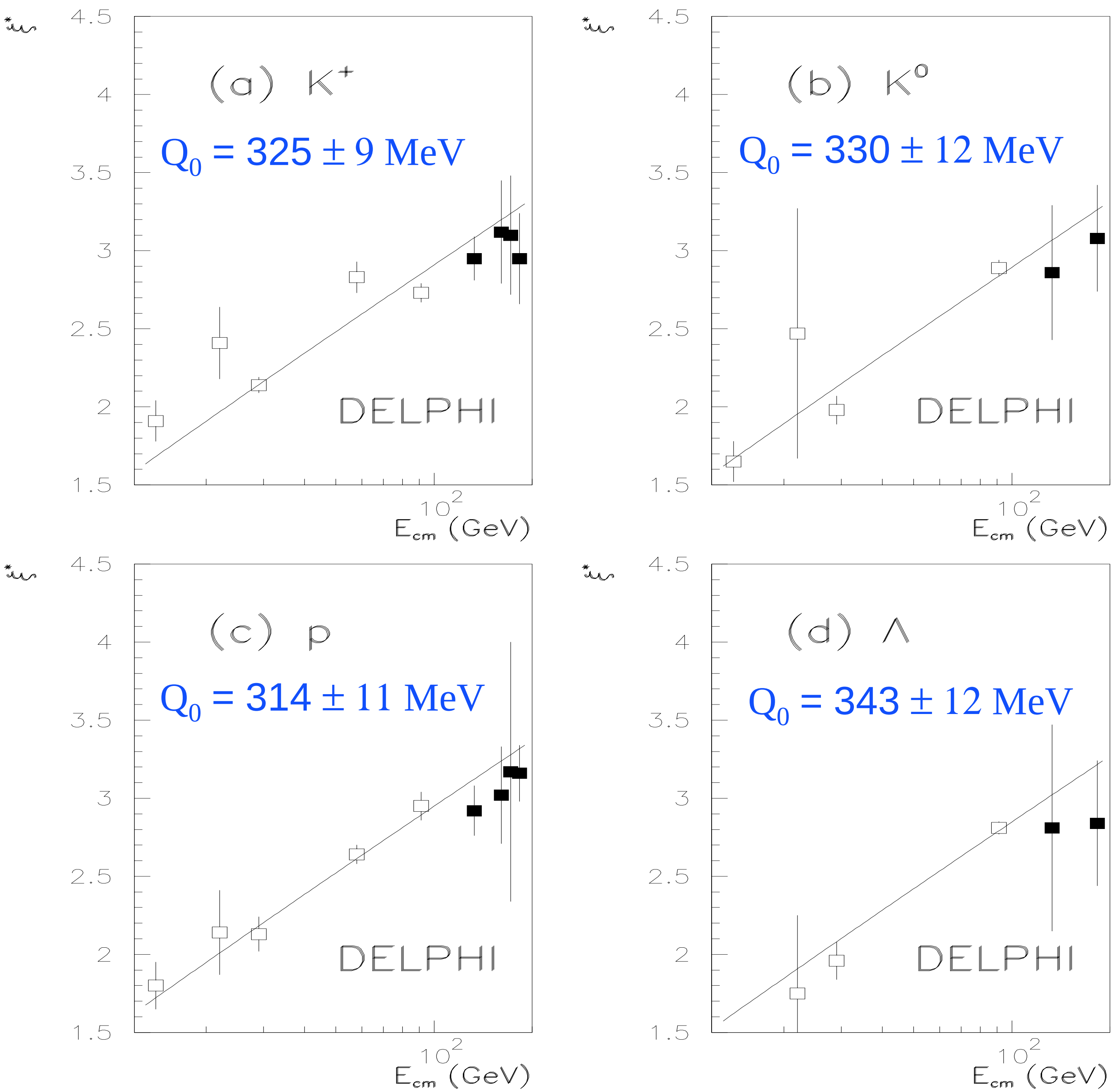


Excellent agreement with MLLA prediction

Production of identified particles

ξ^* evolution

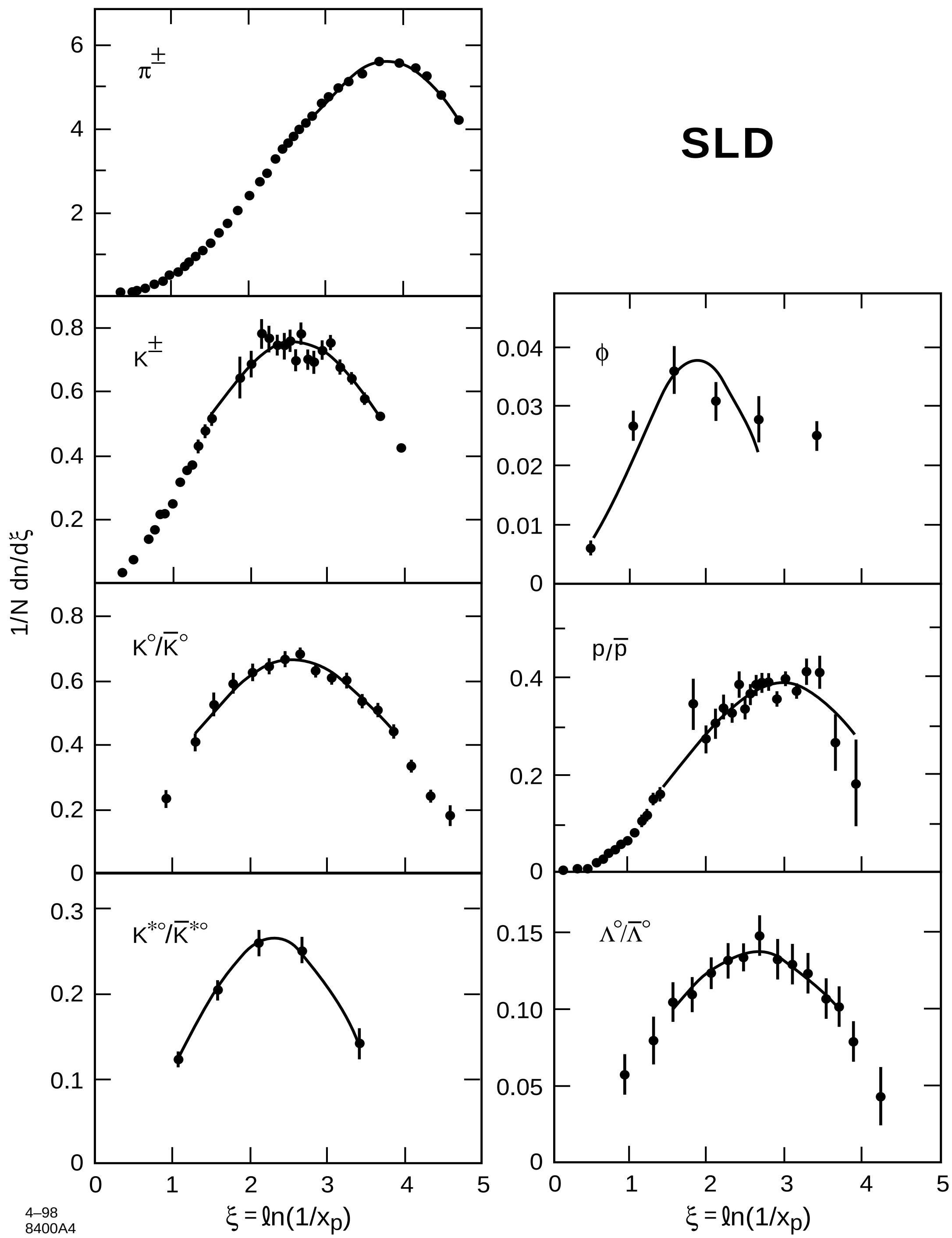
DELPHI Preliminary



- MLLA+LPHD fits the data well (Λ=150 MeV)
- Momentum cut-off parameter Q_0 ~ 330 MeV

Production of identified particles

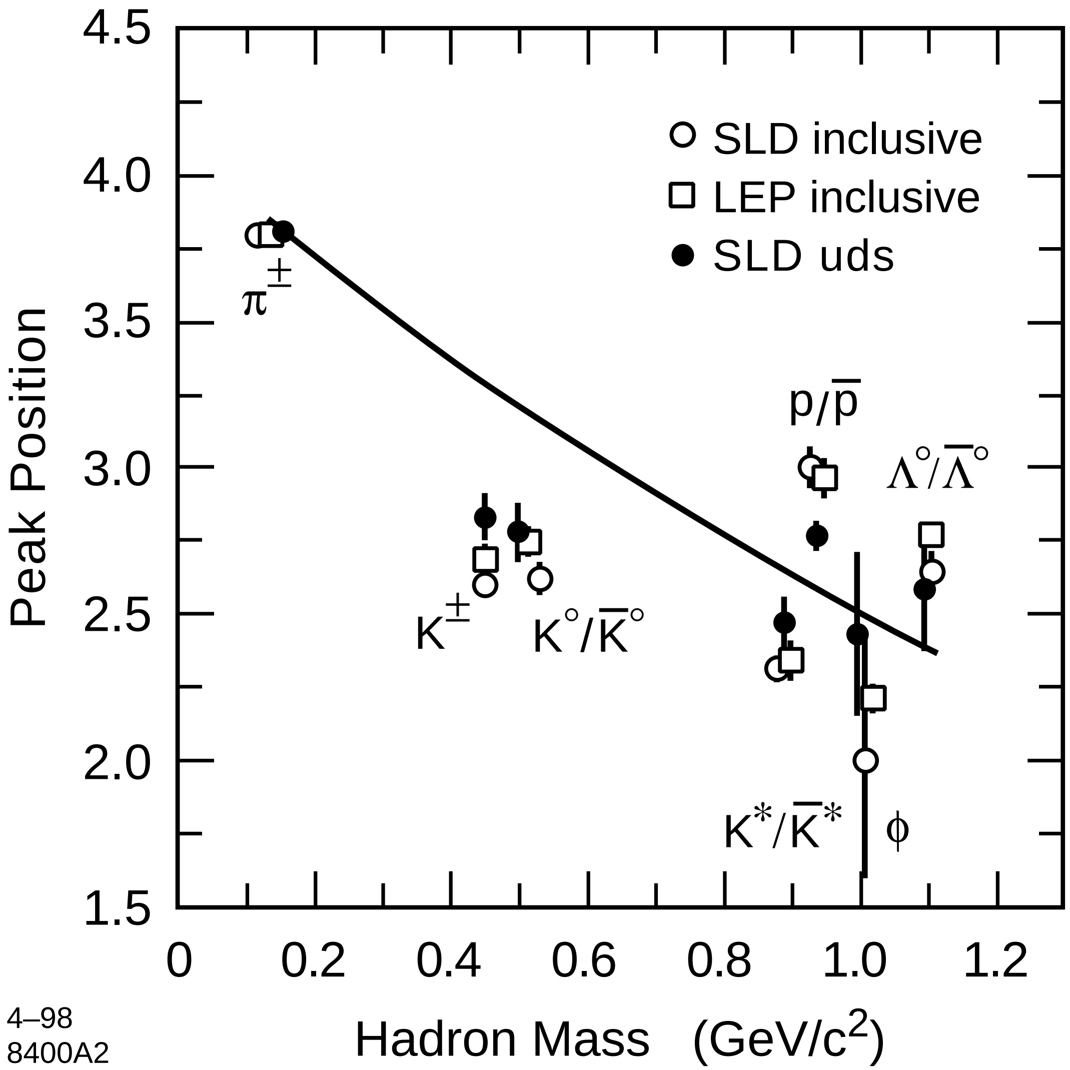
ξ distribution



Production of identified particles

ξ^* vs Hadron Mass

SLD



Except for pions, there is no monotonic mass-dependence of the peak position ξ^*

or

the peak position decreases vs mass differently for mesons and baryons (why? LPHD?)

Invariant Particle Energy Spectra

Results

- The evolution of the fragmentation function at low energies, or high values of ξ, can be studied using the event-normalized invariant spectrum:

$$(1/N_{evts}) \times E d\eta^{\pm}_{tracks} / d^3 p$$

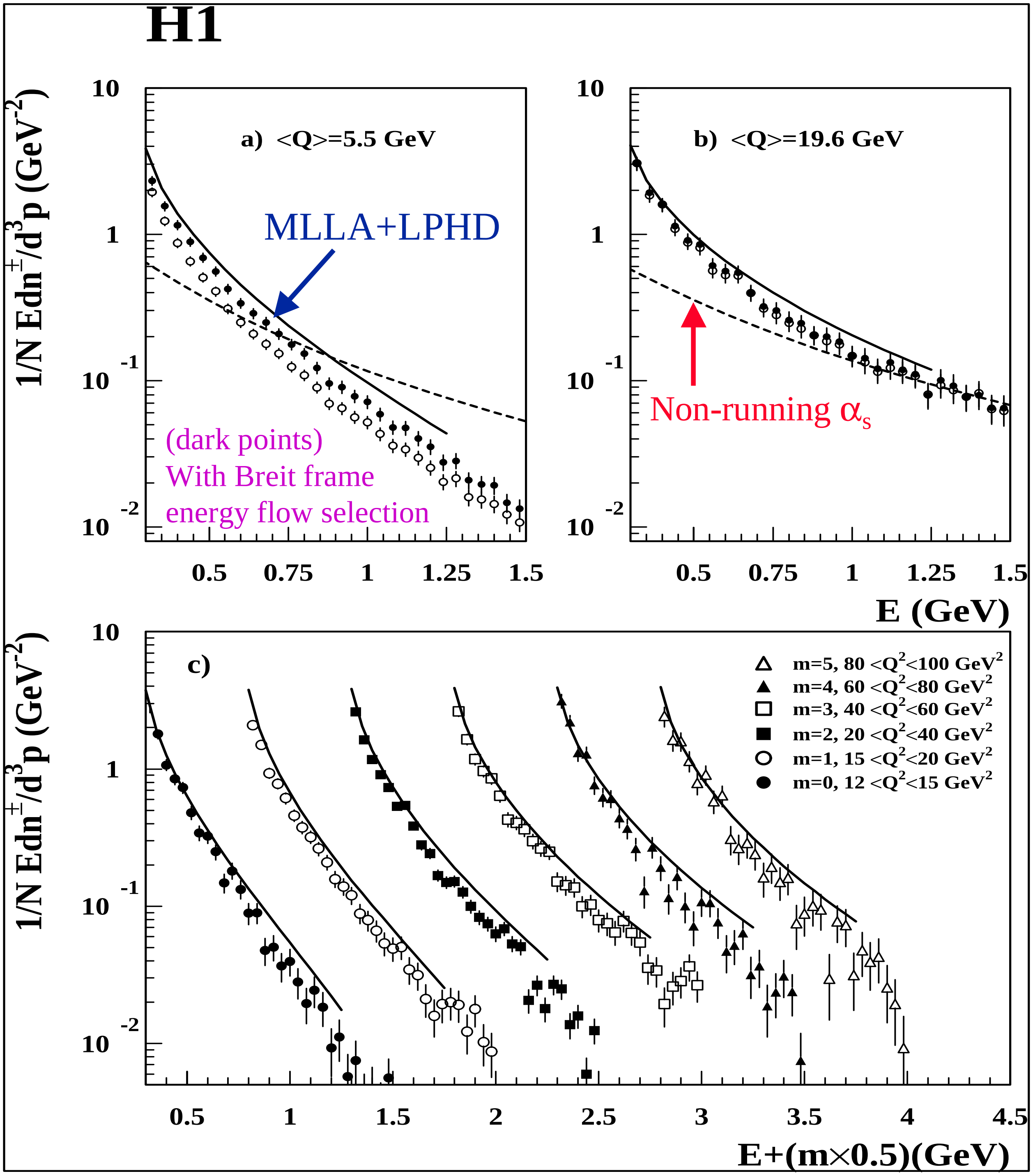
- Due to soft gluon coherence effects, which forbids the multiplication of the soft particles, one expects nearly an energy independent behavior of the soft particle rate

  - The emission rate for gluons with large wavelength does not depend on the details of the jet evolution at smaller distances but it is determined by the color charge of the hard initial partons
    $\Rightarrow$ energy independent

- It provides a nice test of LPHD

Invariant Particle Energy Spectra

Results



MLLA+LPHD fits ep (and e^+e^-) data well.

Invariant Particle Energy Spectra

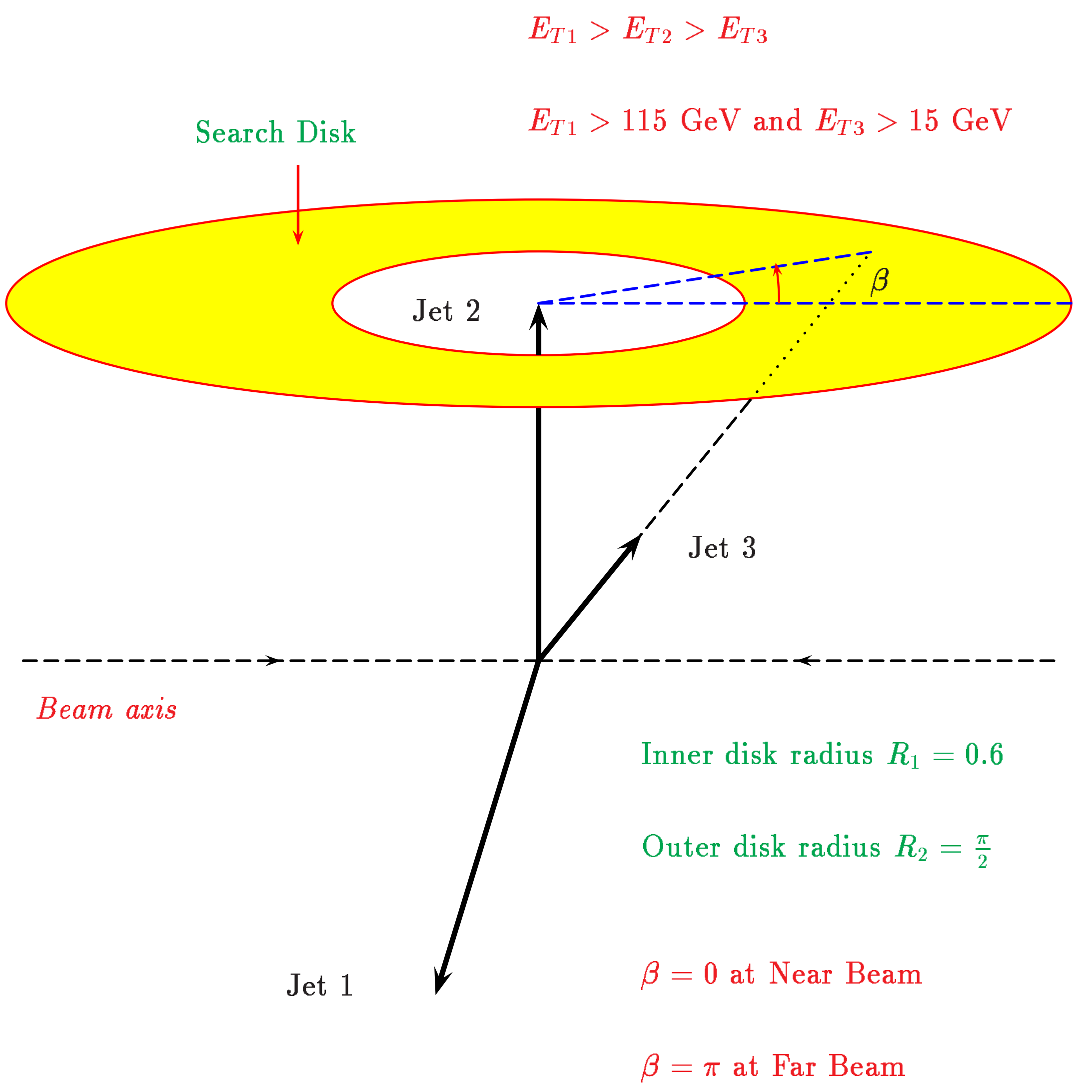
e^+e^-

Multijets Results

$$p\bar{p} \rightarrow 3\,jets + X$$

- Select events with three or more jets

- Measure the angular distribution of "softer" 3rd jet around the 2nd highest E_T jet in the event



- Compare data to several event generators with different color coherence implementations

Monte Carlo Simulations

• Generate high statistics particle/parton level MC samples including detector position and energy resolution effects

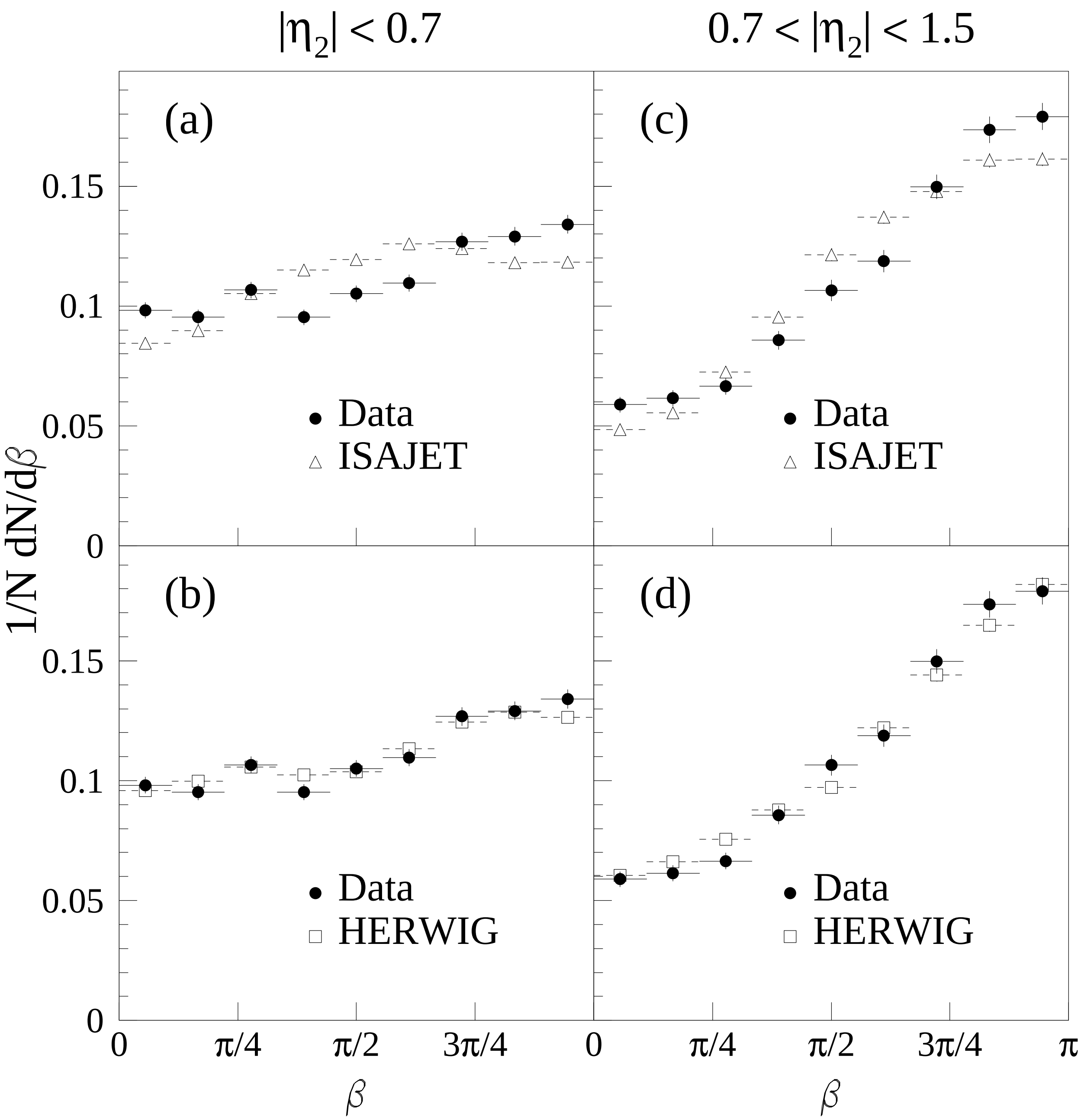
• **Shower-level event generators**:

- ISAJET v7.13
  - Does not include color coherence effects
  - Independent fragmentation
- HERWIG v5.8
  - AO approximation
  - Cluster fragmentation
- PYTHIA v5.7
  - AO approximation (no azimuthal correlations for ISR)
  - AO may be turned off
  - String or independent fragmentation

• **Parton-level pQCD calculation**:

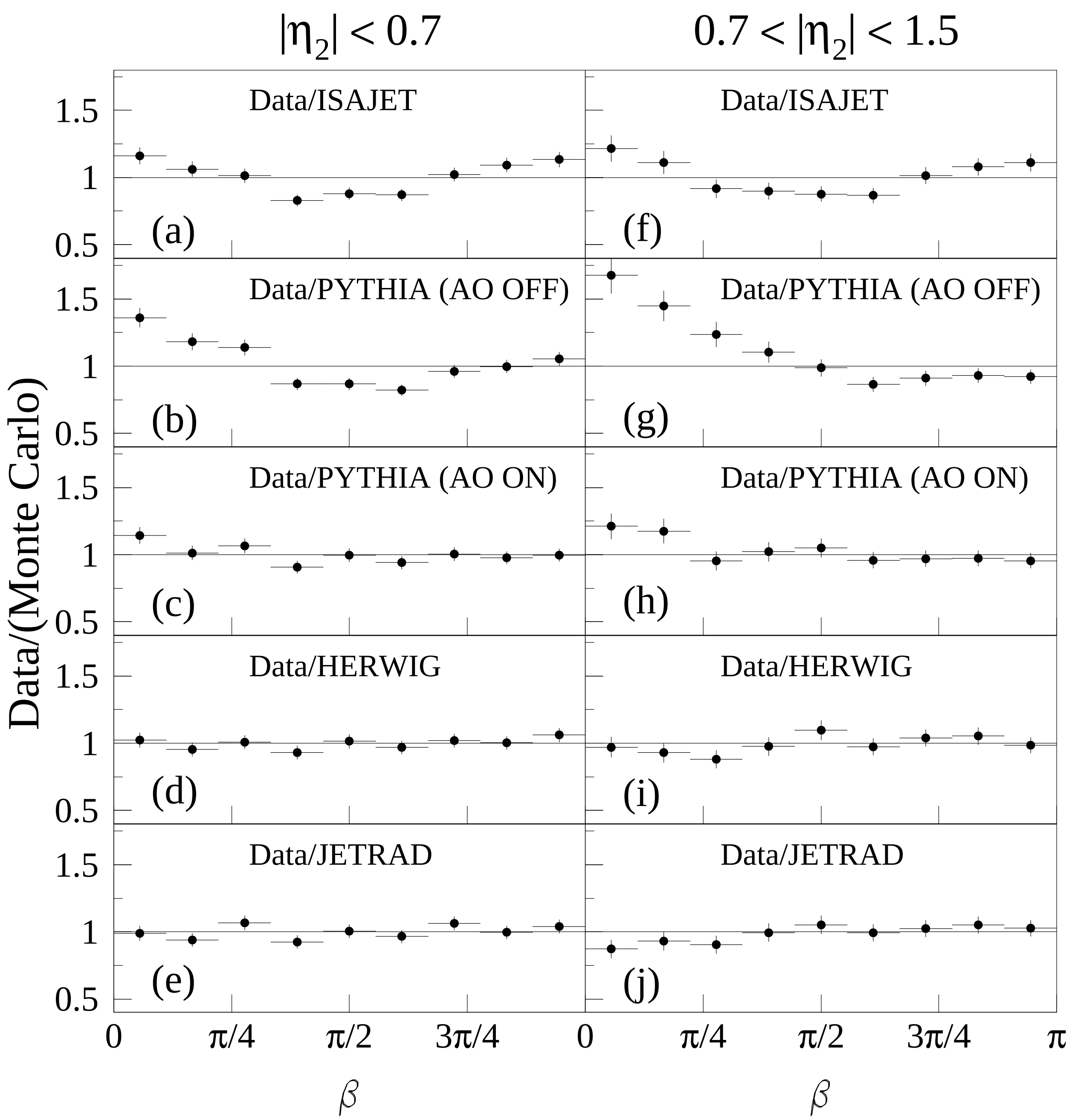
- JETRAD v1.1
  - $O(\alpha_s^3)$ parton level, one loop $2 \rightarrow 2$, tree level $2 \rightarrow 3$ scattering amplitudes
  - No fragmentation

3–jet β distributions



HERWIG agrees with the data distributions

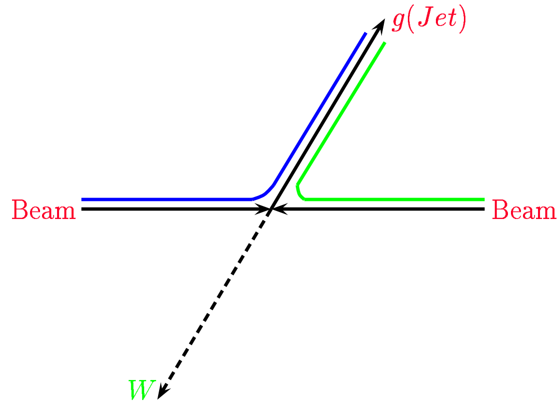
3–jet Data/Monte Carlo



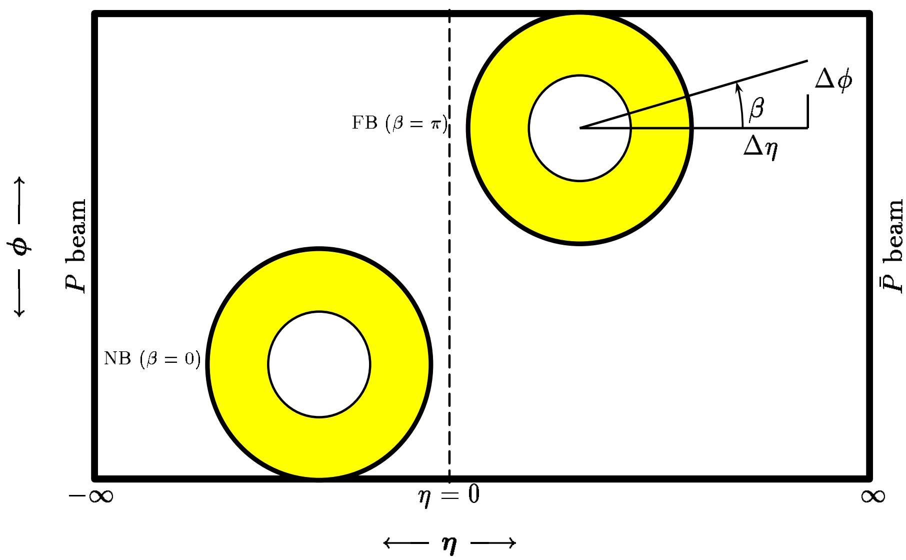
- HERWIG and JETRAD agree best with the data
- MC models w/o CC effects disagree with the data

W+Jet Analysis

Compare pattern of soft particle flow around jet to that around (colorless) *W*



Calorimeter view:



- In each annular region, measure number of calorimeter towers (~ particles) with $E_T > 250$ MeV
- Plot N^{TWR}_{JET} / N^{TWR}_{W} vs. β
- Annuli "folded" about ϕ symmetry axis

  β range: $0 \to \pi$ (to improve statistics)

  $\beta = 0 \to$ "near beam", $\beta = \pi \to$ "far beam"

Search disks: R(*inner*)=0.7, R(*outer*)=1.5

$$\beta = \arctan(\mathrm{sign}(\eta_{W,Jet})\ \Delta\phi / \Delta\eta)$$

W + Jet - Monte Carlo Samples

- **PYTHIA v5.7 Monte Carlo**
  - Full detector simulation
  - Mimic noise by overlaying pedestal data
  - 3 samples with different color coherence:

  “Full coherence”: AO + String Fragmentation

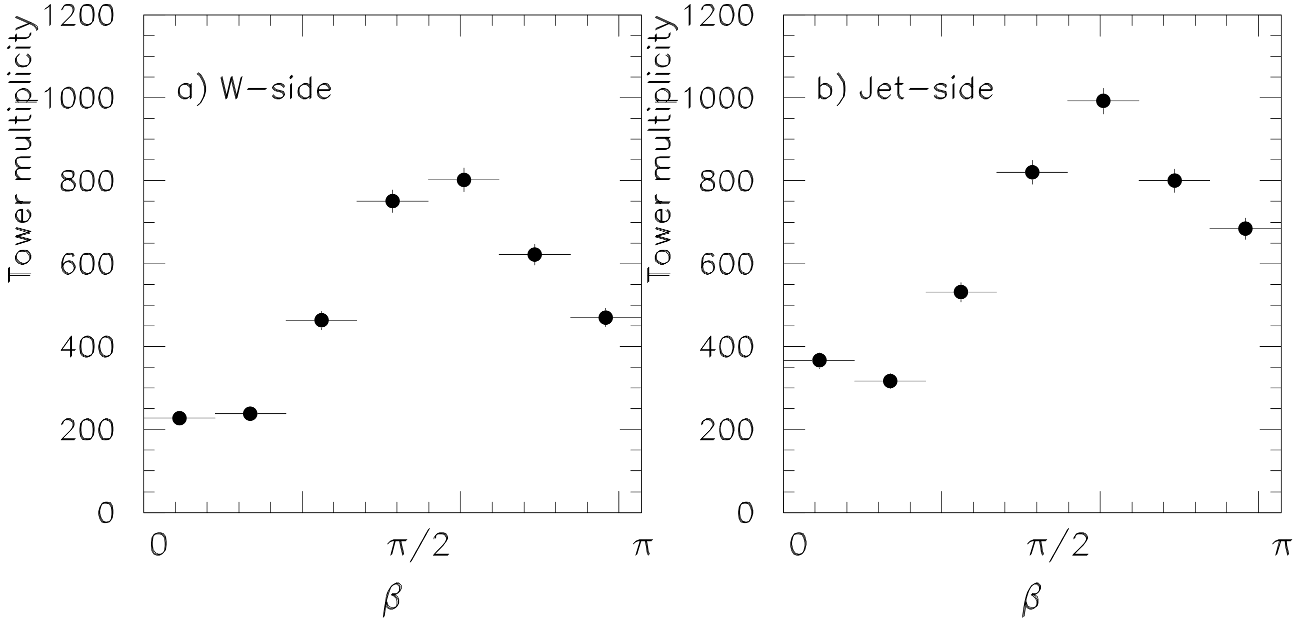
  “Partial”: No AO + String Fragmentation

  “No coherence”: No AO + Independent Frag.

- **Analytic Predictions by Khoze and Stirling**
  - MLLA + LPHD
  - $q\bar{q} \rightarrow Wg$ and $qg \rightarrow Wq$ processes
  - hep-ph/9612351

W+Jet Results

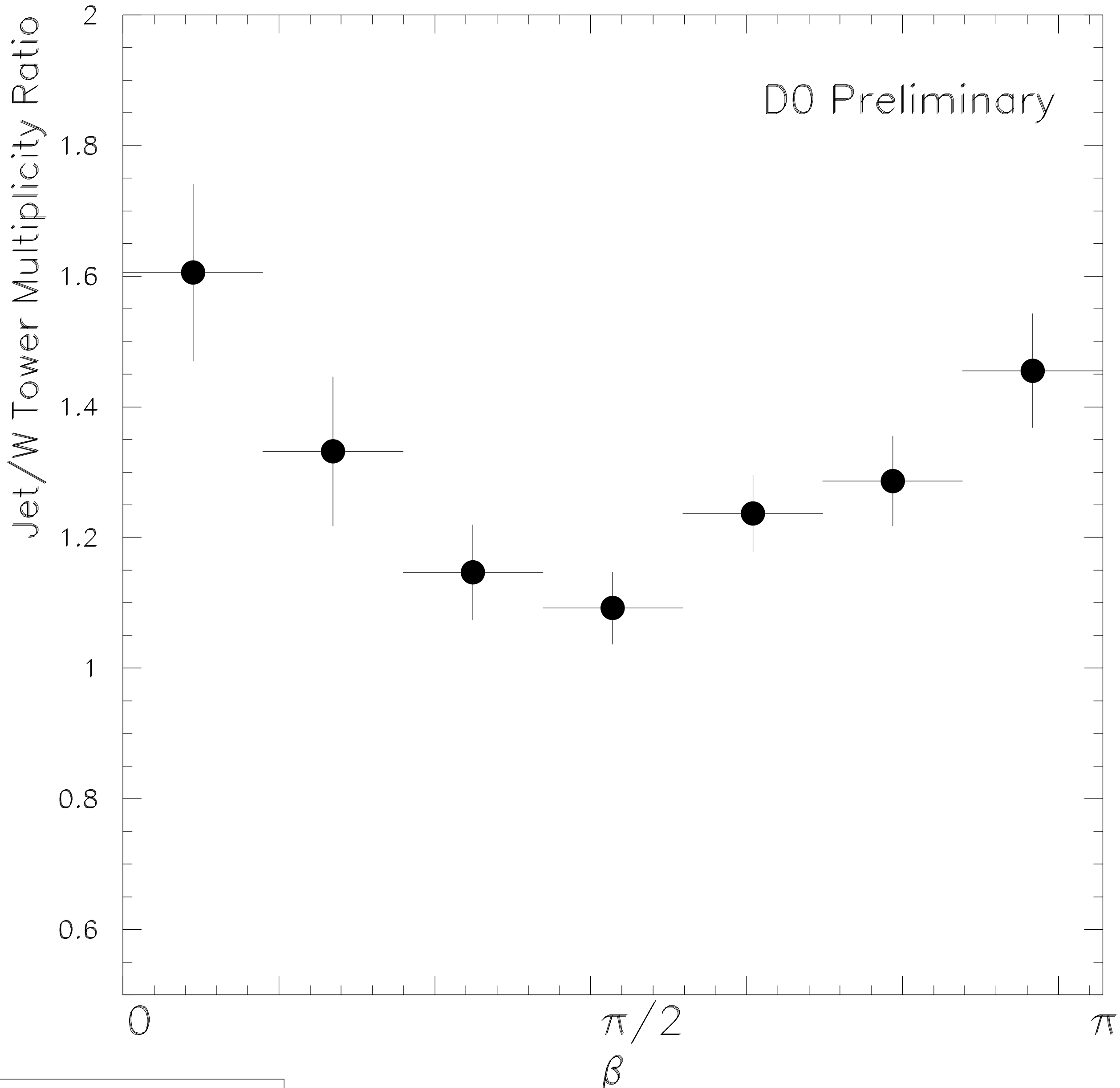
D0 Preliminary



Number of towers (E_T > 250 MeV)

W+Jet Results

D0 Preliminary

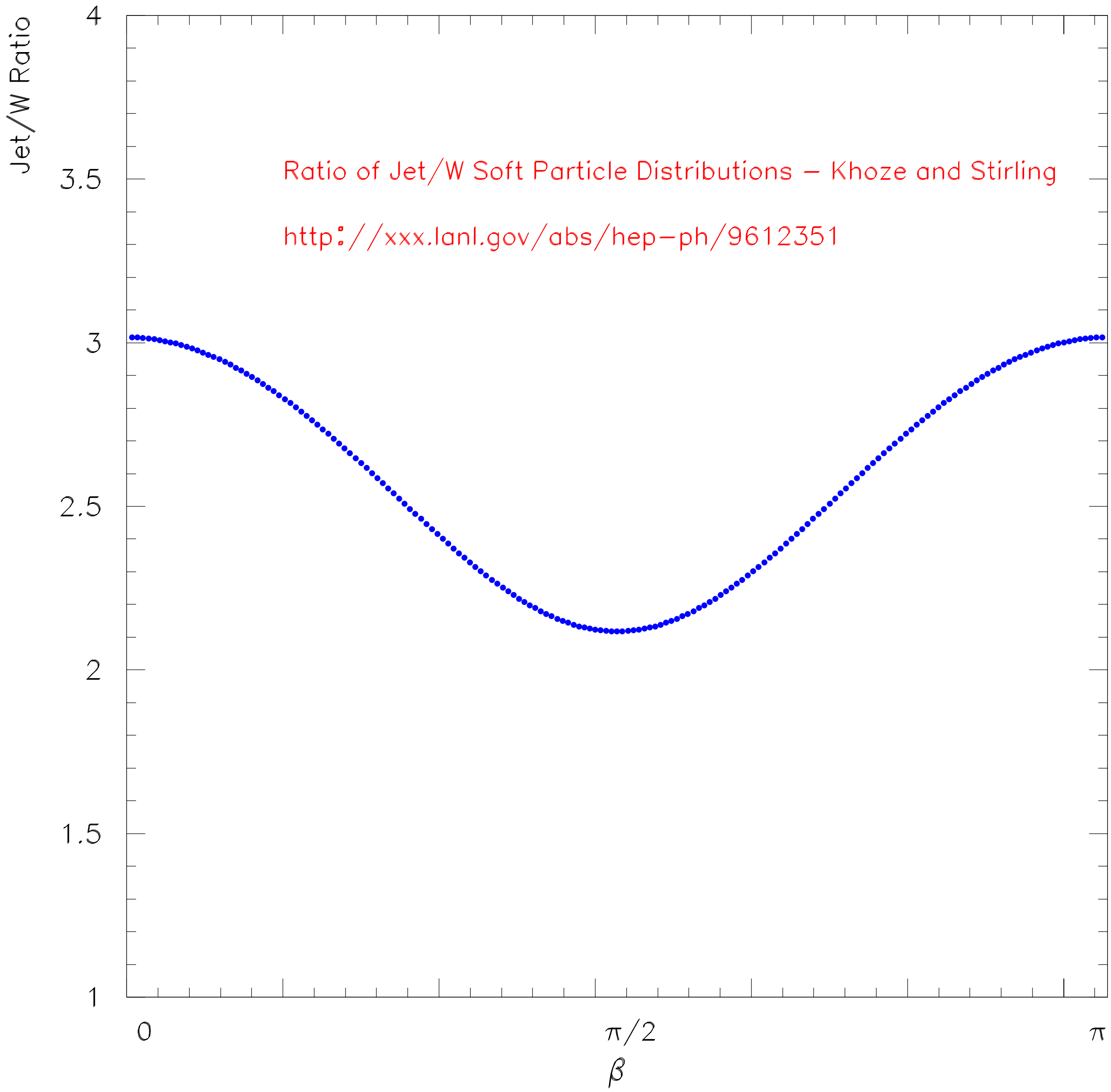


Near beam

Far beam

$N^{JET}_{TWR} / N^{W}_{TWR}$ vs. β

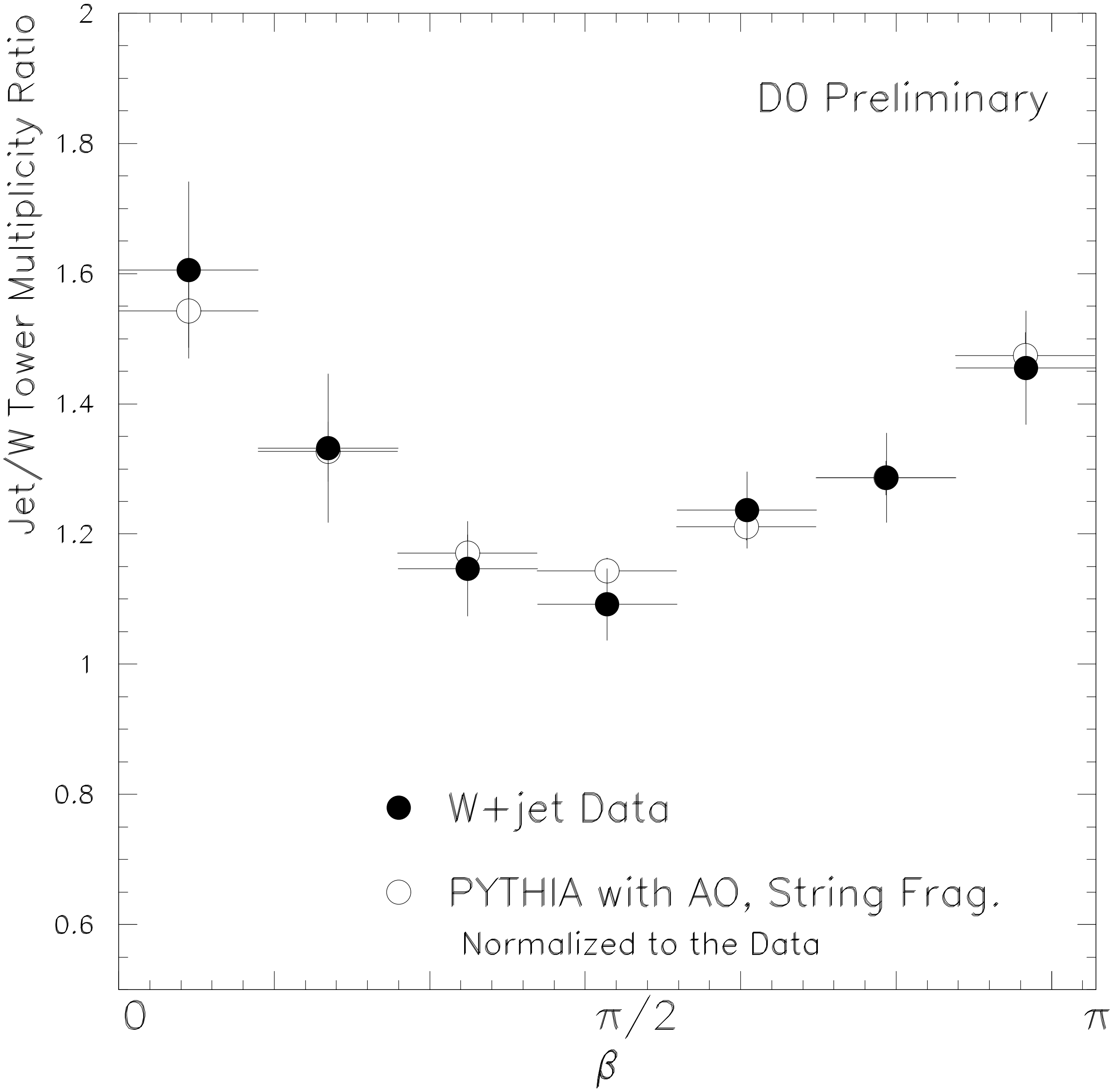
MLLA+LPHD Predictions



W + Jet - D0 Preliminary Results

Comparison to Pythia (Sample I, full coherence)

Angular ordering + String fragmentation

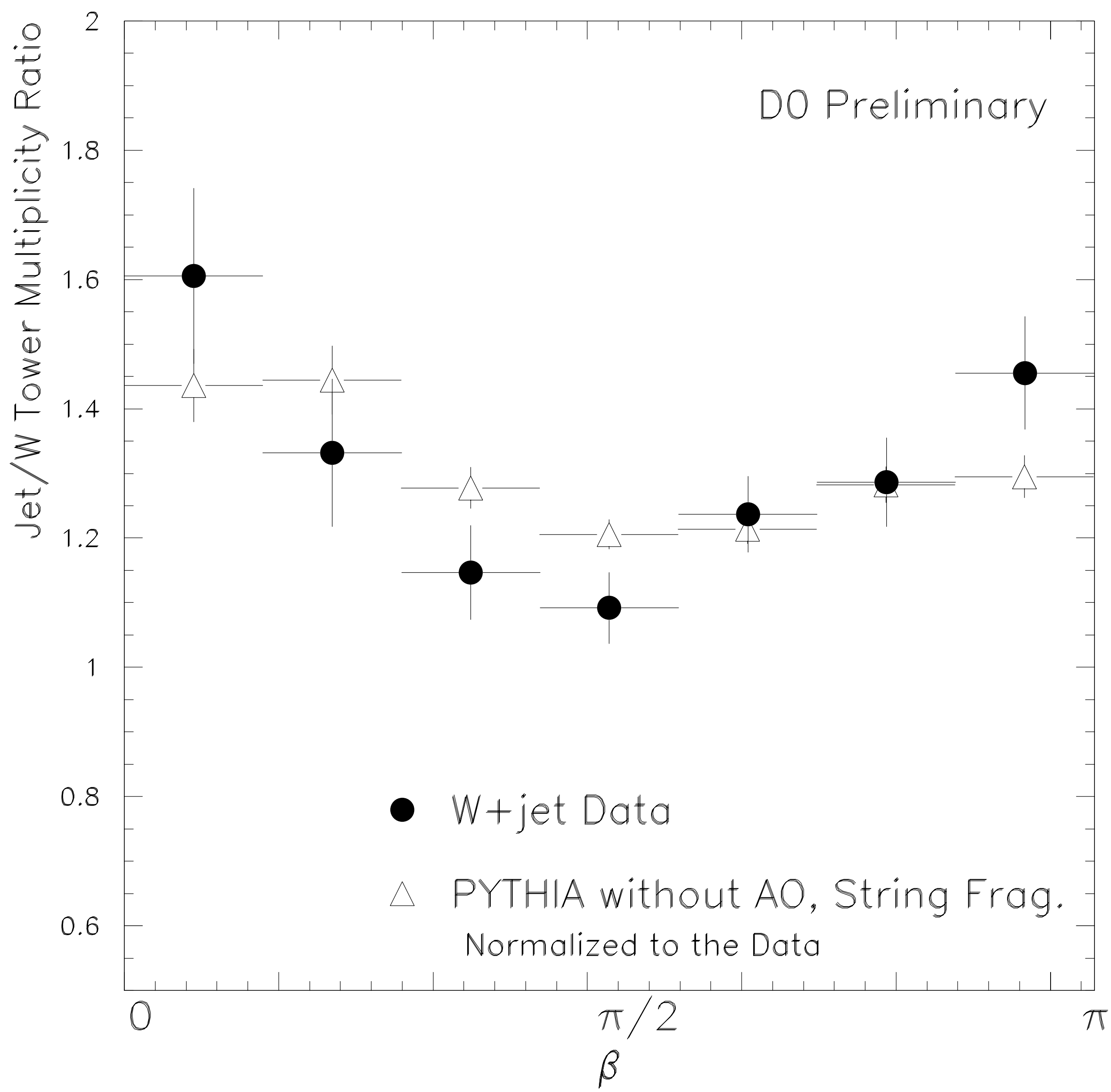


Monte Carlo normalized to data.

W + Jet - D0 Preliminary Results

Comparison to Pythia (Sample II, partial coherence)

NO angular ordering + String fragmentation

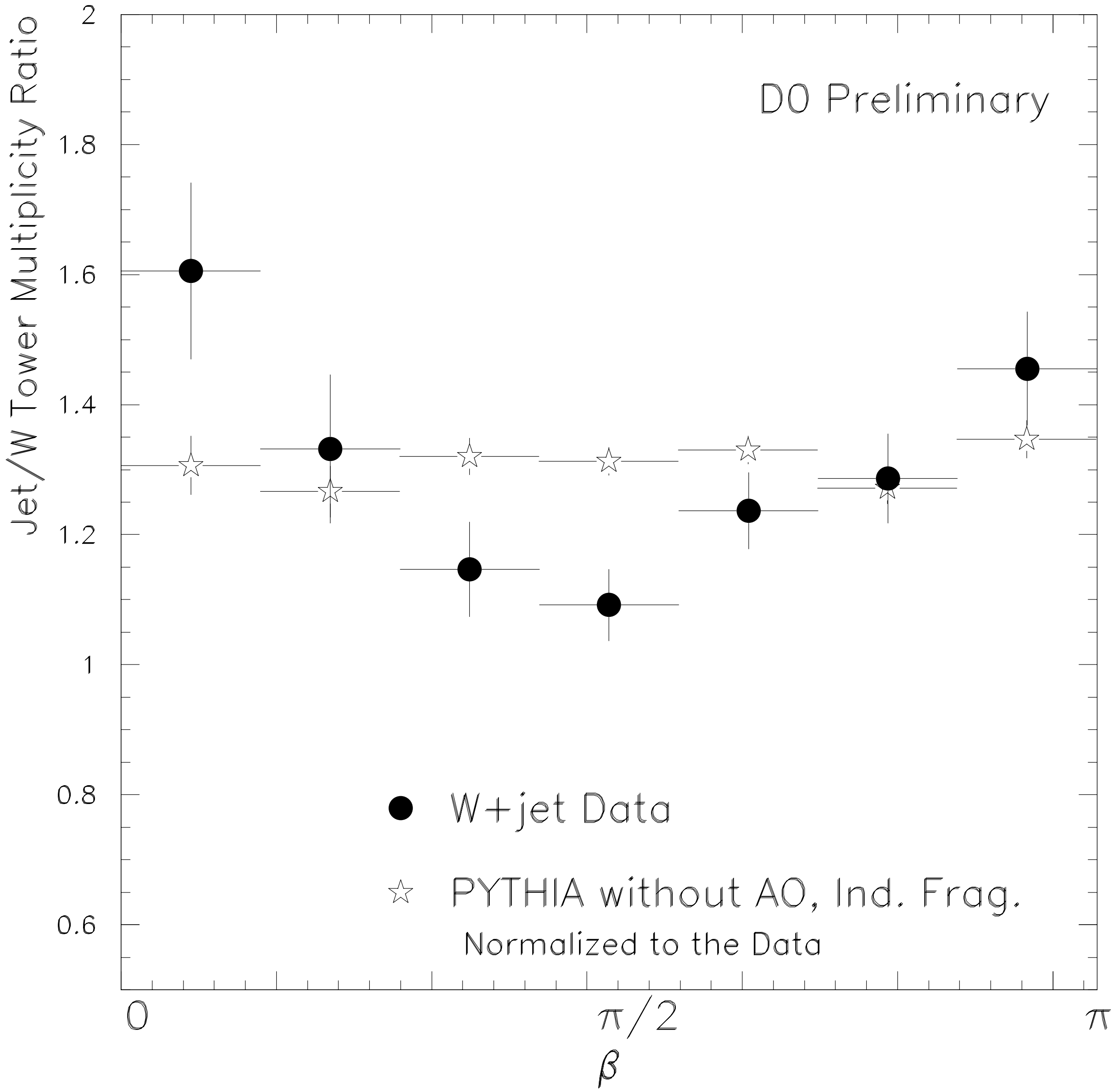


Monte Carlo normalized to data.

W + Jet - D0 Preliminary Results

Comparison to Pythia (Sample III, No coherence)

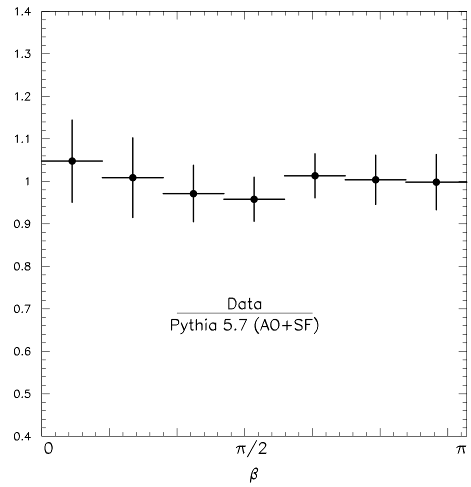
NO angular ordering + Independent fragmentation



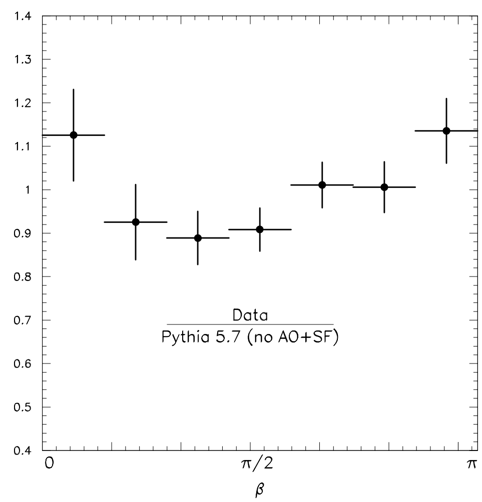
Monte Carlo normalized to data.

W + Jet - D0 Preliminary Results

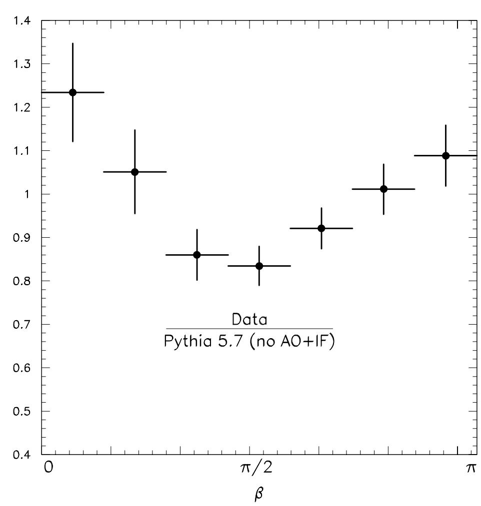
Data / PYTHIA ratios



AO + SF



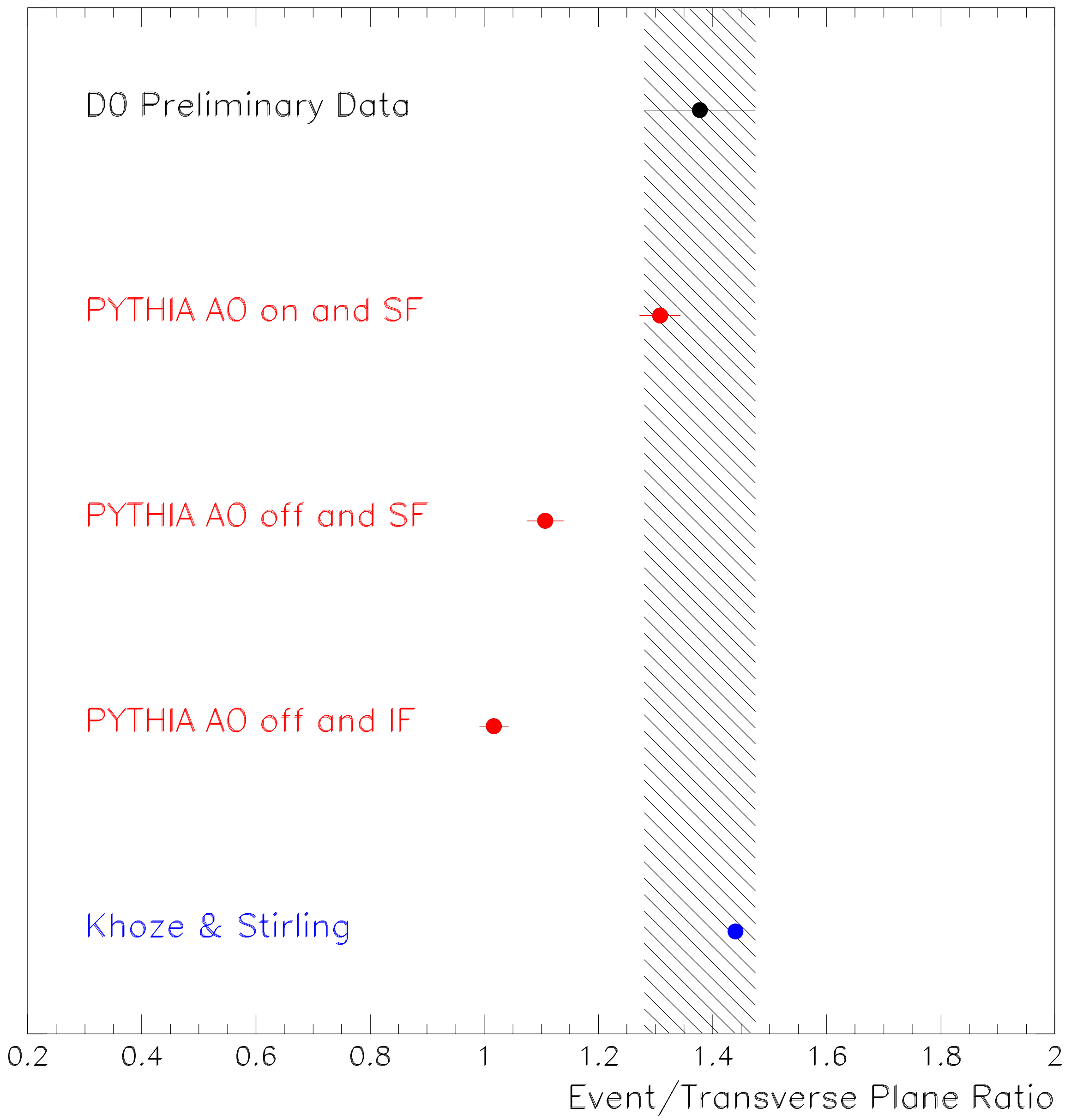
~~AO~~ + SF



~~AO~~ + IF

W+Jet Results

$$\text{Event/Transverse Plane Ratio} = \frac{\text{Jet/W } (\beta = 0 + \pi)}{\text{Jet/W } (\beta = \pi/2)}$$

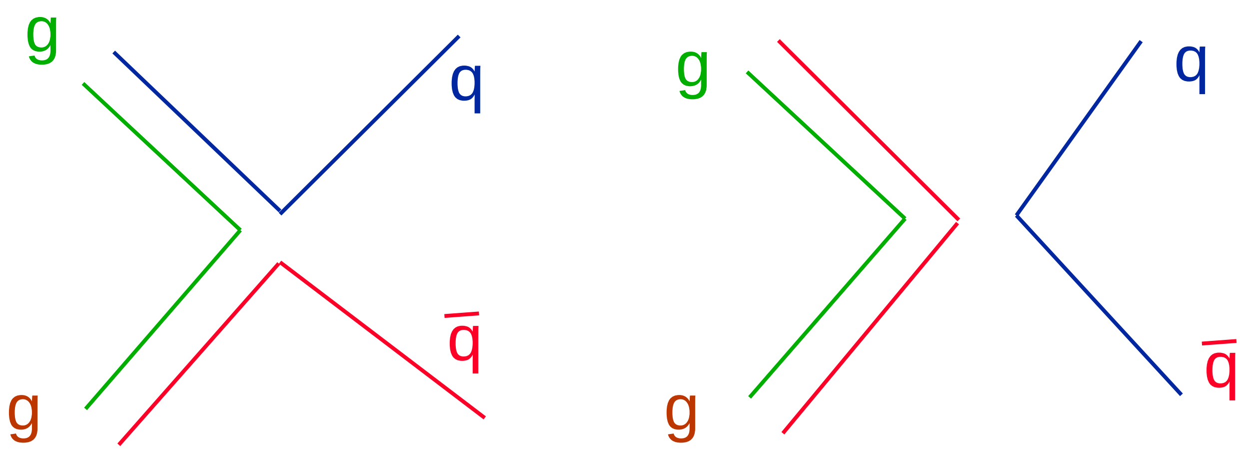


PYTHIA w/ AO & SF ***AND*** MLLA+LPHD agree with Data

OPAL Color Reconnection Results

- Study color “(re)connection” effects in

$$e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}g_{incl} \qquad \text{events}$$



Leading “normal” term (Large-N_c approximation) implemented in the standard versions of MC’s	$1/(N_c^2-1)$ suppressed interference term implemented in latest version of Ariadne

- Sheds light to whether Nature selects a particular configuration at random or some configuration is dynamically favored in forming color singlet states

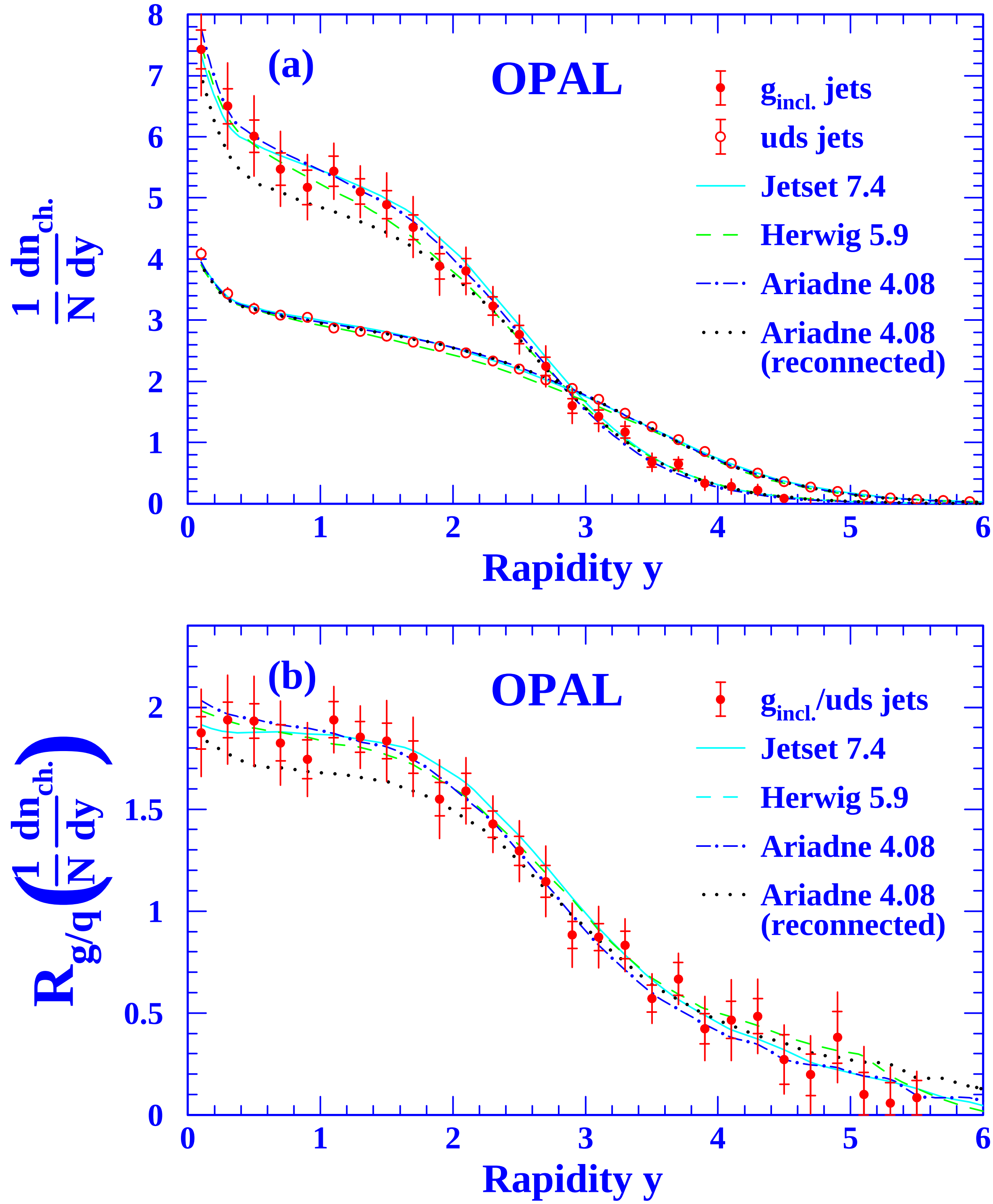
- Such effects, if large, can affect the W mass at LEP-2 (see talk by Monica Pepe-Altarelli)

OPAL Color Reconnection Results

- Select $(q\bar{q})g_{inc}$ events by tagging two quark jets in the same hemisphere of an event. The gluon jet is defined inclusively as all particles in the opposite hemisphere.
- For these type of g_{incl} jets, Ariadne with reconnection predicts fewer (more) particles at small (large) rapidities and energies than standard version or even data.
- Measure the ratio (r_{ch}) of the mean gluon to (light) quark jet charge particle multiplicity for rapidity intervals of $|y|<2$ and $|y|<1$.
- Compare r_{ch} to expectations to MC predictions with and w/o reconnection effects

OPAL **Color Reconnection** **Results**

Preliminary

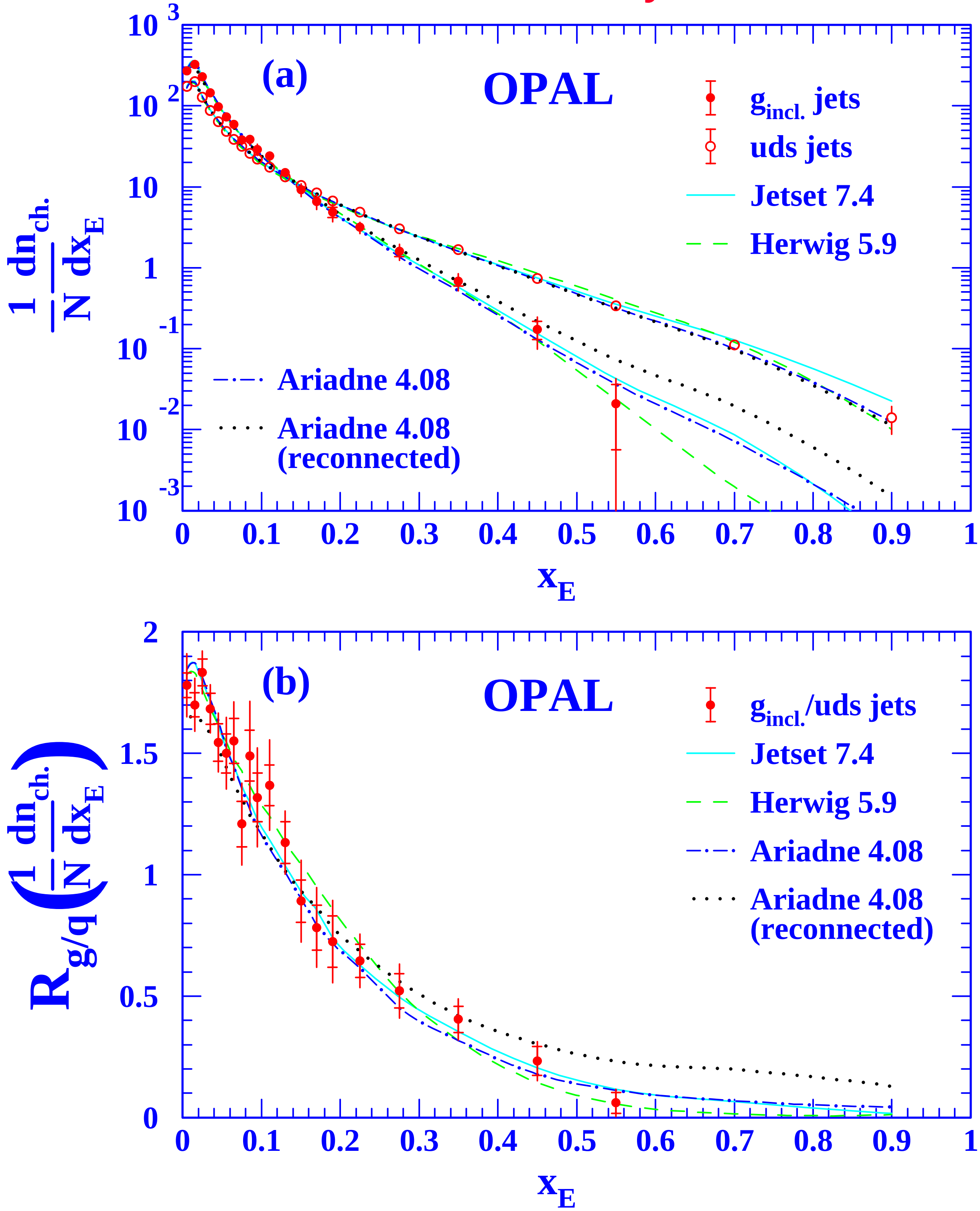


OPAL

Color Reconnection

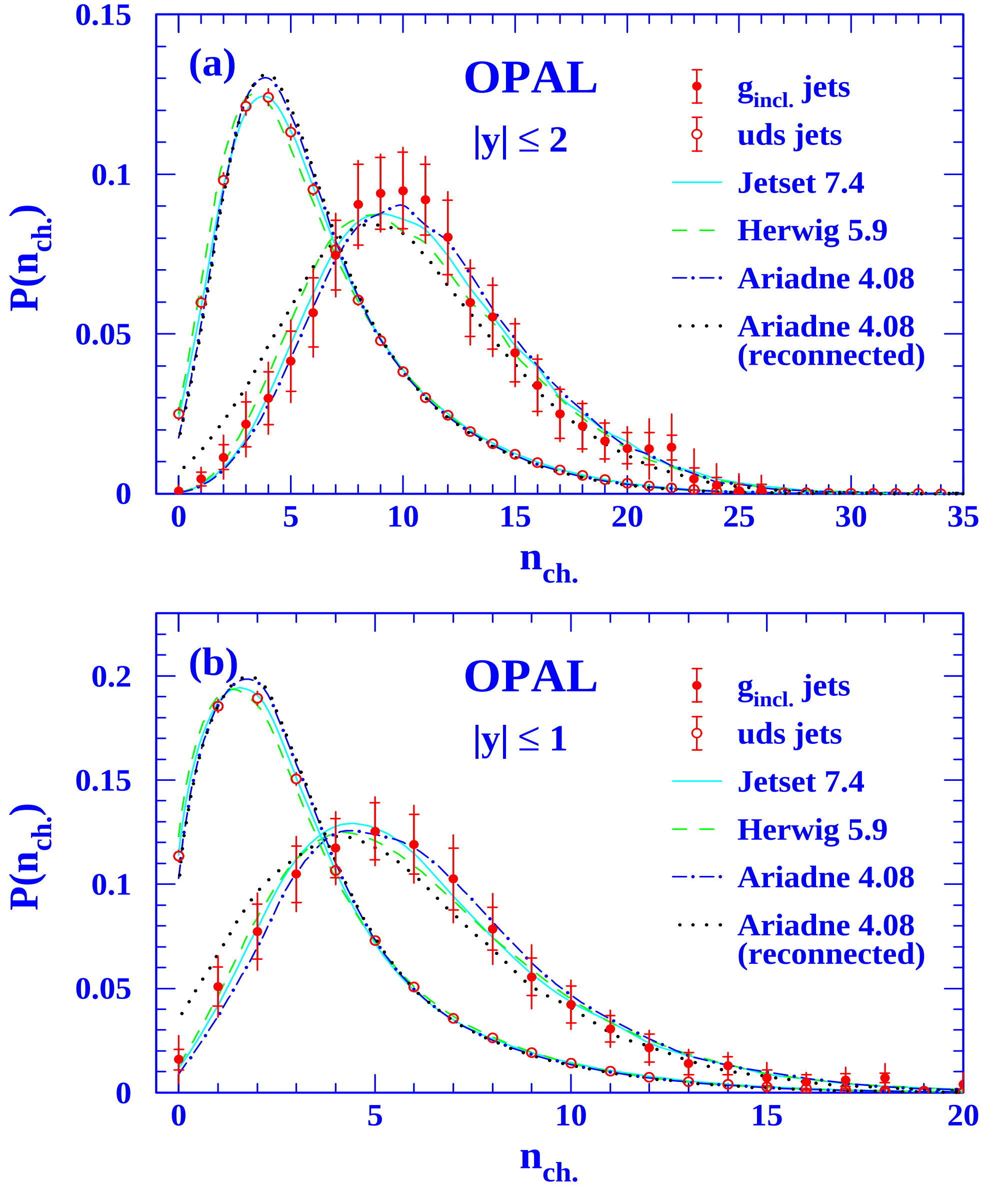
Results

Preliminary



OPAL **Color Reconnection** **Results**

Preliminary



	Probability for $n_{ch}(\lvert y\rvert<2)\leq 5$ in g_{inc} jets	
OPAL Data	$11.0 \pm 1.5 \pm 2.6$ %	
Ariadne (with reconnection)	18.1 %	✖
Ariadne	9.6 %	✓
Herwig	12.7 %	✓
Jetset	10.6 %	✓

OPAL Color Reconnection Results

	r_{ch}
OPAL Data	$1.509 \pm 0.022 \pm 0.046$
Ariadne (with reconnection)	1.42
Ariadne	1.54
Herwig	1.54
Jetset	1.54

	$r_{ch}(\|y\|<2)$
OPAL Data	$1.815 \pm 0.038 \pm 0.062$
Ariadne (with reconnection)	1.69
Ariadne	1.88
Herwig	1.85
Jetset	1.85

	$r_{ch}(\|y\|<1)$
OPAL Data	$1.87 \pm 0.05 \pm 0.12$
Ariadne (with reconnection)	1.75
Ariadne	1.96
Herwig	1.91
Jetset	1.89

Summary

- Inclusive charged hadron fragmentation functions as measured at HERA, LEP, and TEVATRON are in agreement with MLLA+LPHD predictions.
- Possible mass dependence effects on the production of identified hadrons may be challenging LPHD.
- Invariant particle energy spectra from HERA and LEP show that the soft limit for a variety values of Q is essentially independent of Q as predicted by MLLA+LPHD.

Summary continues

- Observation of interjet color coherence effects in W+Jets and Multijet events.
  - Data are in agreement with perturbative QCD calculations
  - Data support LPHD hypothesis
  - Color coherence effects at this level can be accommodated in parton shower generators
- It has been suggested that the methodology employed in the W+Jets analysis can provide a tool for distinguishing different topologies of color flow in hard processes (e.g. Higgs production - hep-ph/9805490) from the QCD background.
- No sign of color "reconnection" effects in $e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}g_{incl}$ events.